Tertiary Treatment of Municipal Sewage via Slow Sand Filtration

by

Samer Said Al-Adham

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

CIVIL ENGINEERING

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UMI
300 North Zeeb Road
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KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

This thesis, written by

SAMER SAID AL-ADHAM

under the direction of his thesis committee, and approved by all the members, has been presented to and accepted by the Dean, College of Graduate Studies, in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

Thesis Committee

Chairman (Dr. S. Giray Velioglu)

Member (Dr. Rashid I. Allayla)

Member (Dr. Shaukat Farooq)

Dr. Rashid I. Allayla
Department Chairman

Dr. Abdullah S. Al-Zakri
Dean College of Graduate Studies

Date : 30/5/1989

بسم الله الرحمن الرحيم

DEDICATION

This work is dedicated:

* To the sun of hope and source of giving

My Mother

* To the emblem of sacrifice and symbol of strong will

My Father

ACKNOWLEDGEMENT

First and foremost, praise and thanks be to Almighty **ALLAH**, the most Gracious, the most Merciful; and peace be upon His Prophet.

I wish to express my sincere appreciation to Dr S.Giray Velioglu, my Major Thesis Adviser, for his invaluable and continuous guidance and encouragement throughout this study. I also wish to thank the other members of my Thesis Committee, Dr Rashid I. Allayla and Dr Shaukat Farooq, for their cooperation and helpful suggestions.

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THESIS ABSTRACT

Name of Student : SAMER SAID AL-ADHAM

Title of Study : TERTIARY TREATMENT OF MUNICIPAL SEWAGE VIA SLOW SAND FILTRATION

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ABSTRACT

This study is a field evaluation of slow sand filtration as a tertiary treatment process at pilot-scale. It was found out that slow sand filtration is , indeed, very effective in removing contaminants from secondary effluents. In particular, the bacterial removal levels were exceptional to an extent that the filtrate would easily qualify for unrestricted irrigation. In view of the experimental results, 0.16 m/hr is suggested as a suitable hydraulic loading for the design of similar systems in Saudi Arabia. At this hydraulic loading the observed average removals of BOD, SS, turbidity and total coliform bacteria were 86, 69, 88, and over 99%, respectively, and the length of the filtration run was about 20 days. It was confirmed that most of the purification is occurring at the top layers of the filter such that even a sand bed depth of 35cm yielded significant levels of contaminants removal. It was also observed that the presence of algae in the filter influent is a very important condition as it adversely effects the filter performance.

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خلاصة الرسالة

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خلاصة

هذه الدراسة هي تقييم حقلي للترشيح البطيء كوسيلة للمعالجة الثالثة لمياه المجاري بواسطة مرشح بقياس تجريبي . أستنتج أن الترشيح البطيء هو حقا فعال في ازالة الملوثات من نواتج المعالجة الثانية . خصوصا , ازالة البكتيريا كان رائعا لدرجة ان المياه المرشحة تصلح بسهوله للاستخدام في الري بشكل غير مقيد . على ضوء نتائج الدراسة , اقترحت الحمولة الهيدرولوكية ١٦ر٠ متر في الساعة كحمولة مناسبة لتصميم مرشحات مماثلة في المملكة . بهذه الحمولة الهيدرولوكية , نسبة الازالة المرصودة من المواد العضوية القابلة للتحلل بيولوجيا , المواد العالقة , الغشاوه . وبكتيريا الكوليفورم كانت ٨٦ ، ٦٩ ، ٨٨ وأكثر من ٩٩٪ , بالمماثلة , وكان طول فترة الترشيح حوالي ٢٠ يوما . الدراسة أكدت بأن معظم التنقية تحصل في الطبقات العليا من المرشح لدرجة أن عمق ٣٥ سم من الرمل أدى الى مستوى عالي في ازالة الملوثات . بالاضافة الى ذلك , استنتج أن وجود الطحالب في المياه المتدفقة الى المرشح مسألة هامة لأنها تؤثر عكسيا على فعالية المرشح .

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران – المملكة العربية السعودية

آيار / ١٩٨٩م

Chapter 1

INTRODUCTION

The general scarcity of water in arid regions, such as Saudi Arabia, and the high costs of developing new water supplies are the two major factors responsible for the need to conserve water by reusing wastewater effluents. The practice of water conservation has reached to such a level of importance that, nowadays, it is routinely included in national development policies. For example, according to the third five-year development plan, the Kingdom of Saudi Arabia is expecting to recycle 730 million cubic meters per year of wastewater, by the year 2000 (37). The major reuse of wastewater worldwide is for irrigation, amounting to approximately 60% of the total, while the second largest reuse, accounting for about 30% , is for industrial cooling and process waters(39).

Most wastewater treatment schemes cover conventional secondary treatment, even in developed countries. The secondary effluent characteristics are mainly defined in terms of biochemical oxygen demand (BOD), total suspended solids (TSS) and fecal coliform

(FC) concentrations. The secondary effluent standards, in general, dictate that the 30-consecutive-day arithmetic means for BOD and TSS should be less than 30 mg/l while for the fecal coliforms the limit is 200 FC per 100ml (39). The major concern of wastewater reuse is related with health aspects. Along these lines the bacteriological standards set for restricted irrigation (i.e., foddler crops) range from 1000 to 5000 FC per 100ml,however, for unrestricted irrigation the standard is 100 FC per 100ml (20,26). Hence, if direct reuse of secondary effluents is to be considered, it is required to process these effluents further (i.e., employ tertiary treatment).

Tertiary treatment is an additional step to remove more contaminants from wastewater than what is usually taken out by the conventional secondary wastewater treatment. It includes microstrainers, filtration (slow or rapid), chemical precipitation, carbon adsorption or reverse osmosis (7,21,27,39). The selection of a tertiary treatment process depends mainly on the target water quality. Since microbial quality is of utmost importance in wastewater reuse, a process with effective bacterial removal, such as slow sand filtration, has been adopted in this study.

Slow sand filters are traditionally used for the purification of potable waters due to their ability to produce a high quality filtrate. They are called slow filters because the rate of filtration is much lower than rapid filters (i.e., 0.1-0.4 m/hr as opposed to 5-21 m/hr). As a result,however,their land area requirement is much larger.This constitutes the main disadvantage of slow sand filters. Other reported disadvantages are their poor performance at low temperatures and for highly turbid waters (8,11,14,24,32,33). It should be realized that the first two disadvantages are not valid for Saudi Arabia while the third is of little concern in view of the characteristics of secondary effluents. Coupling this assessment with the following advantages of slow sand filters:

- stable and effective TSS and bacterial removal,
- simplicity in construction, and
- low cost of operation and maintenance,

it is concluded that slow sand filtration would be an appropriate tertiary treatment process for the Kingdom.

The present study is an experimental work to evaluate the slow sand filtration process as a tertiary treatment unit. The performance of the filter, in terms of relevant quality parameters, was evaluated under various hydraulic loadings. The bacterial removal and the head loss build-up in the sand bed were recorded during each experiment. In view of the experimental observations, an attempt is made to establish the operational conditions for such units, applicable to Saudi Arabia.

Chapter 2

LITERATURE REVIEW

2.1 WASTEWATER FILTRATION

Filtration can be defined as a physical, chemical and (in some instances) biological process for separation of nonsettleable impurities from water or wastewater by passing it through porous media. Although filtration has been used in the treatment of potable water since early 19th century, its application to wastewater is a relatively recent practice. Stringent effluent requirements increased interest in wastewater filtration dramatically over the past two decades. At present wastewater filtration is considered among the well-established processes for the tertiary treatment of effluents from wastewater treatment plants (5,7,9,21,28,35,36,38,39).

In very simple terms, the filtration process is carried out within a box into which a porous medium and an underdrain collection system is placed. The filters for treating wastewater are essentially similar to those employed for the treatment of potable water.

However, the processes have significant differences mainly due to the influent characteristics. In general, solids present in secondary effluents, i.e., influent to wastewater filters, have been observed to be heavier and more variable in particle sizes (21,35,36). Filtration, basically, consists of two distinct operations: filtration and cleaning. As filtration progresses the solids removed within the filter medium accumulate resulting in restriction of passage of water (i.e., head loss build-up) and/or decrease in suspended solids removal efficiency (i.e., deterioration of quality). The filtration operation is stopped when the allowable limits for head loss or effluent suspended solids (usally referred to as "filter breakthrough") is reached. It is desired to have these events occur at the same time. Upon termination, the filter bed has to be cleaned and prepared for the next filtration cycle.

A wide variety of methods exist for filtration, including microstrainers and precoat filters,however, granular media filters are by far the most commonly adopted method of filtration (19,20,21,35). Granular media filters can be classified according to (21):

- the direction of flow: upflow or downflow filters,

- the types of filter beds: single or multi-layer filters,
- the driving force: gravity or pressure filters,
- the rate of filtration: constant or declining rate filters.

Each of the above filter types has its own advantages in addressing a particular problem (21,35). For example, multi-layer filters were developed in order to achieve a more effective use of the filter bed depth. In other words, they allow the suspended solids to penetrate deeper into the bed, and thus, use more of the solids removal capacity available within the filter. In single medium filters, however, most of the solids removal takes place in the top few centimeters of the bed. Deeper penetration of solids results in a decrease in the rate of head loss build-up, therefore, it leads to longer filter runs. A further classification of granular media filters is with respect to the magnitude of the filtration rate being "rapid" or "slow" .

2.2 SLOW SAND FILTRATION

In recent years, there has been a tendency to consider the slow sand filtration as an old-fashioned treatment process and it has been replaced by rapid-gravity or other high-rate filtration methods. However, in some circumstances, slow sand filtration can, not only be the simplest and cheapest, but also be the most efficient process for water treatment. The success of slow sand filters for the treatment of potable water is widely agreed on and it is still the chosen technology of water purification even in some highly industrialzed cities as well as in rural areas. For example, they cover 72 hectares of land area for the treatment of London's potable water. In addition, their major advantage over the other processes is, using local skills and materials which make them extremely suitable for developing countries. Moreover, they are much more efficient than high-rate filters in removing microbial contaminants (8,11,12,14,33).

During the operation of slow sand filters, a layer of inert deposits and biological matter forms on the surface of the sand bed. This layer is referred to as the Schmutzdecke,(a German word meaning "dirt-layer"). Biological growth also occurs within the sand bed. Both the Schmutzdecke and the biological growth within the filter bed play a significant role in the purification mechanism of slow sand filters (4,8,14,19,33).

The cleaning process of slow sand filters is done by removing the top 2-4 cm of the sand bed (i.e., Schmutzdecke) upon termination of the filtration phase. Evidently, the sand depth will be decreased by 2-4 cm following each cleaning operation which will lead to the minimum sand bed depth (approximately 48-60 cm, (4,8,14,33)). At this stage, the filter has to be resanded. The resanding is usually done as shown in Figure 2.1 . Approximately the top 30 cm of the sand bed will be removed out and kept in a nearby container. Then, the filter will be refilled with new sand to a level 30 cm below the maximum sand bed depth. After that, the sand kept in the container will be added on to the top of the new sand. This procedure is expected to reduce the time of Schmutzdecke formation or ripening period since the "old" sand contains all the organisms needed for proper biochemical functioning (14,33).

Slow sand filters are different from the rapid sand filters in terms of several aspects. Table 2.1 gives a comparison of the general features of both slow and rapid filters(9). The slow sand filters are commonly operated at a constant rate filtration,however, in some instances, they are operated at declining rate filtration. This is normally conducted by closing the inlet

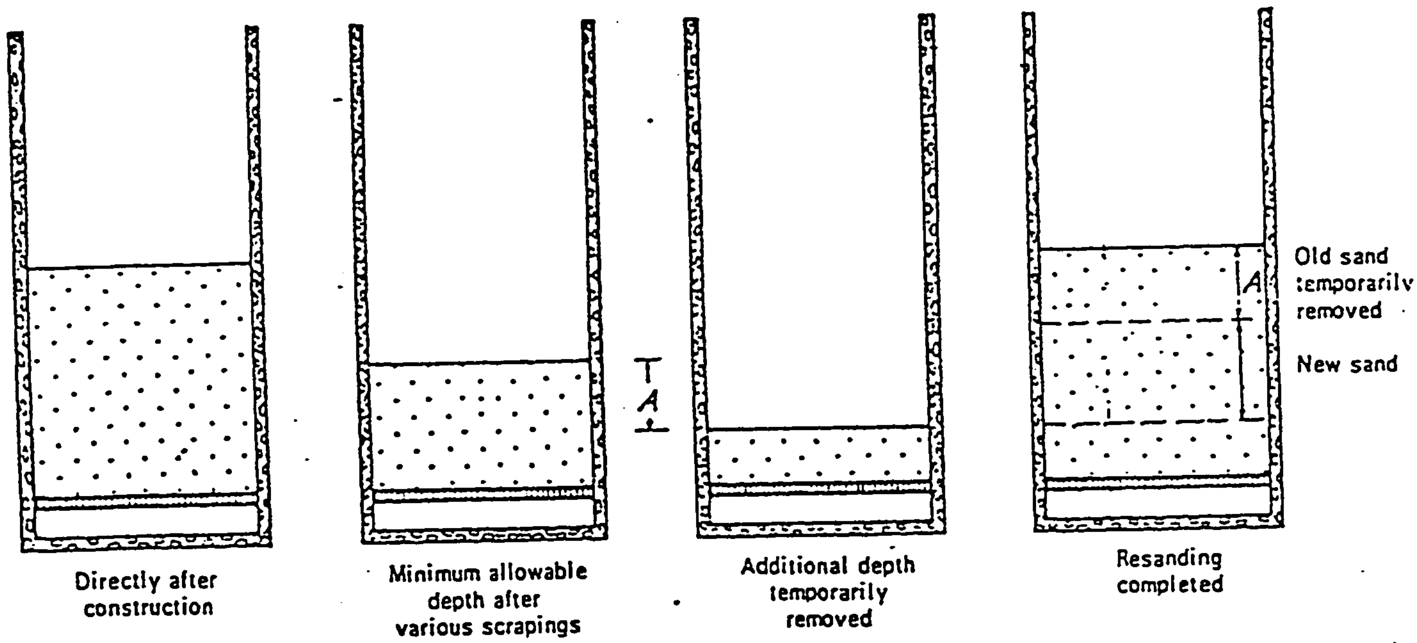

Figure 2.1: Resanding of a Slow Sand Filter (33)

Table 2.1: General Features of Conventional Slow and Rapid Sand Filters (9)

	Slow Sand Filters	Rapid Sand Filters
Rate of filtration	0.1 to 0.4 m/hr	4 to 21 m/hr
Area of the filter	Large, 2000 m^3	Small, 40-400 m^3
Depth of bed	30 cm of gravel, 90 to 110 cm of sand	30 to 45 cm of gravel, 60 to 70 cm of sand
Size of sand	ES 0.15-0.35 mm UC 3 or less	ES 0.35 mm or more UC 1.5 or less
Grain size distribution of sand	Unstratified	Stratified
Loss of head	6 cm initial to 120 cm final	30 cm initial to 275 cm final
Length of run between cleanings	20 to 60 days	12 to 72 hr
Method of cleaning	Scraping off surface layer	Backwashing
Amount of water used in cleaning	0.2 to 0.6% of water filtered	1 to 6% of water filtered
Cost of construction	Relatively low	Relatively high
Cost of operation	Relatively low	Relatively high

valve but keeping the outlet valve open during overnight shutdown. In doing so, the top water level and thus, the head for filtration will slowly decrease, resulting in a decrease of the filtration rate. Usually the outlet level is positioned slightly above the sand bed level in order to avoid the possibility of having negative pressures within the sand bed. Negative pressures will consolidate the sand bed and may result in release of dissolved gases resulting in formation of air pockets within the bed. Both cases have adverse effects on the filtration operation (8,14).

Intermittent operation of slow sand filters (by closing both inlet and outlet valves overnight) is not advisable. This is because the top water becomes stagnant and the the lower levels of water are then in contact, for some period, with a highly biologically active layer of sand (i.e., Schmutzdecke). This may lead to anaerobic conditions if the dissolved oxygen is depleted which in turn can create unpleasant tastes and odors, and more importantly to unacceptable deterioration of the bacteriological quality of filtered water (8,11,14,32).

2.2.1 Components

Slow sand filters can be divided into the following basic elements as depicted in Figure 2.2 (8,11,14,31):

I- ***Filter box:*** The filter box is usually rectangular or cylindrical in shape with vertical walls over 3m in height, made of reinforced concrete or steel and it has a concrete floor. It should be watertight to avoid loss of water. The filter box essentially serves as the housing for the following:

a) *Top* (*Supernatant*) *Water Reservoir*: The water above the sand bed, with a common depth of 1-1.5 m, provides sufficient head to obtain the desired filtration rate for an appreciable length of filter run.

b) *The Filter Medium* (*Bed*): Although various materials have been employed as a filter medium in slow sand filters, sand is by far the most common. The sand used is characterized by its Effective Size (ES), d_{10}, which is defined as the diameter for which 10% of the sand is finer by weight, and its Uniformity Coefficient (UC), which is defined as the ratio of d_{60} to d_{10}(13).

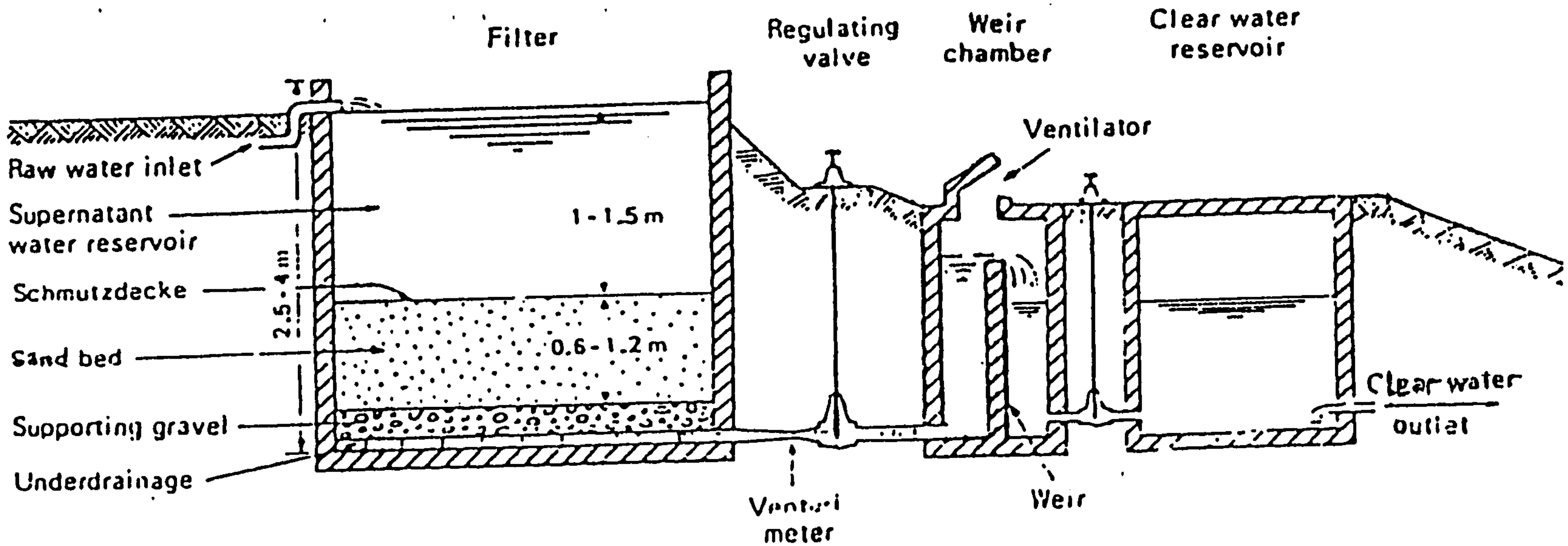

Figure 2.2: Details of a Slow Sand Filter (14)

The typical range of ES is 0.15-0.35 mm while UC is suggested to be less than 3.0, preferably less than 2.0 (8,14,23). The depth of the filter bed needed for proper functioning of the purification process is between 60-70 cm, so the commonly used initial bed depth is between 1.0-1.2 m to allow for a good number of filter cleanings before resanding.

c) *The Gravel*: The supporting gravel layer is laid under the sand bed. It serves a dual function of preventing the sand from entering into the underdrains and ensuring uniform abstraction of the filtered water. It consists of a number of graded layers with largest size at the bottom and smallest at the top. The total depth of all layers is generally between 20-50 cm (8,11).

d) *The Underdrain system* : Finally, an underdrain system is placed at the bottom of the filter. Its main function is to collect and direct the filtered water to the filter outlet. It can take various forms, such as perforated pipes, open-joint bricks and porous unglazed pipes. Figure 2.3 illustrates the different types of underdrain systems commonly used. A photograph of a typical underdrain system consisting of open-joint bricks (i.e., Figure 2.3(A)) and the supporting gravel is given in Figure 2.4 (29).

II- *Weir Chamber and Clear Water Reservoir*: These constitute auxiliary structures that would facilitate the operation of a filtration system. The underdrain system directs the water into the weir chamber. The weir chamber is equipped with a partition wall which serves as an overflow weir. The height of the weir is adjusted to be just above the maximum sand surface level, to avoid the development of negative pressures within the sand bed, as mentioned earlier. The weir chamber is open at the top to allow for contact with atmosphere. As the water flows over the weir it is aerated which gives the water an opportunity to restore any oxygen depletion that might have occurred during the filtration operation. The clean water reservoir is basically a storage reservoir for filtered water. It is no different than any service reservoir.

III- *Control Valves*: The slow sand filter is provided with control valves to regulate the flow of water.

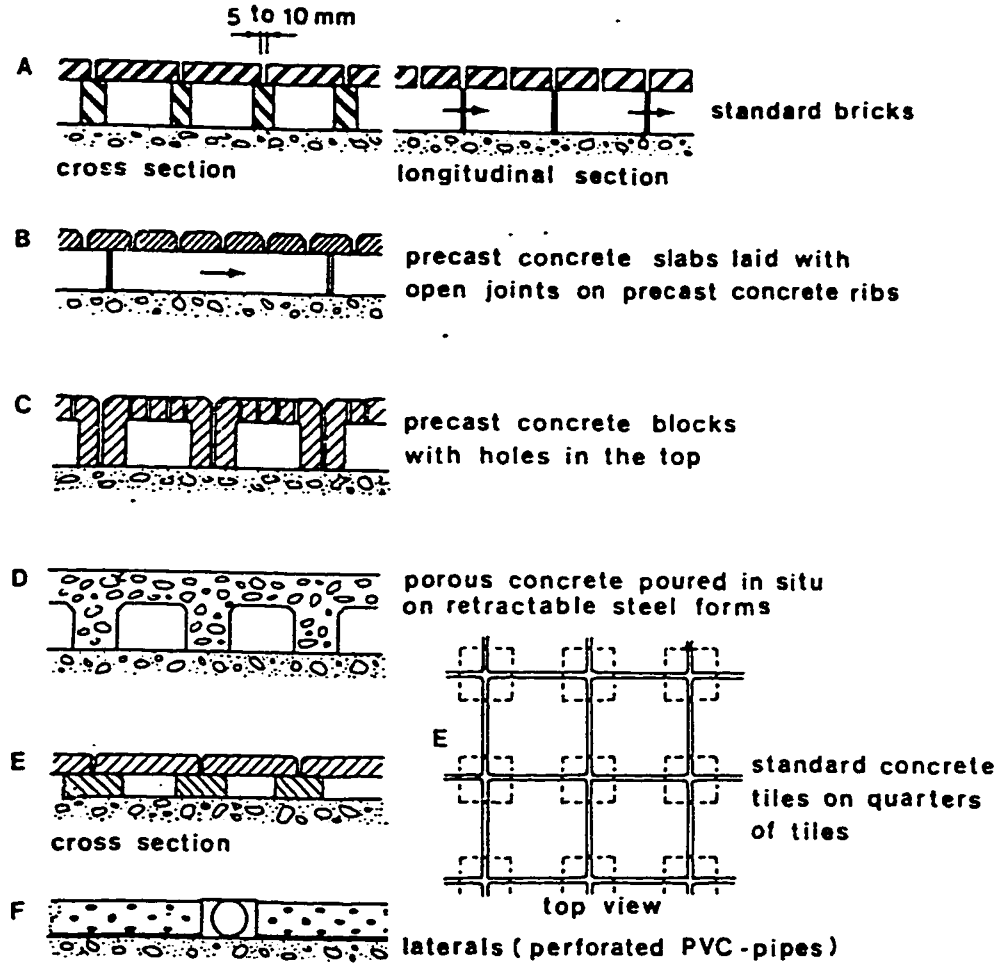

Figure 2.3: Different Types of Underdrain Systems (29)

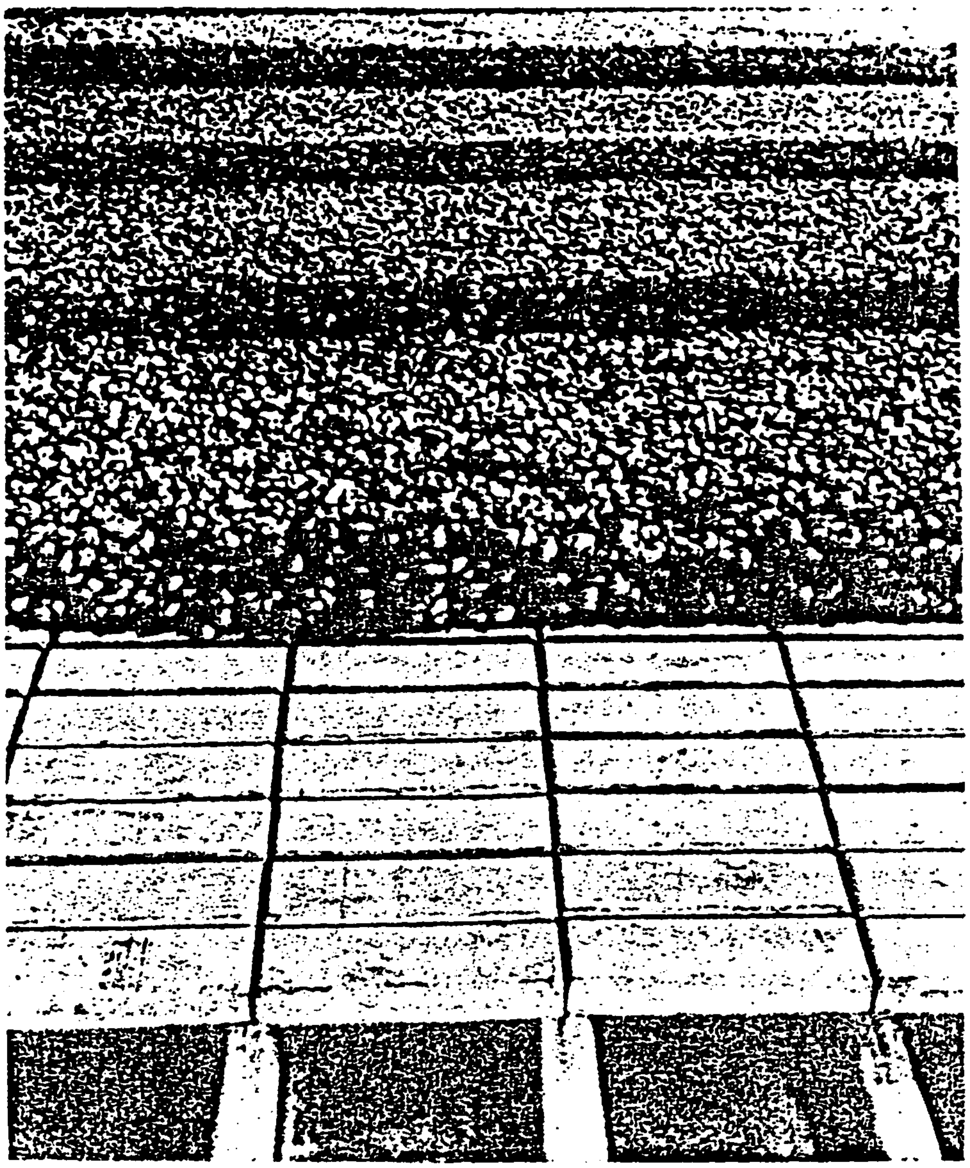

Figure 2.4: Typical Crose-Section of the Underdrain and Supporting Gravel (29)

For clarity of illustration, Figure 2.5 shows the points of use of such valves in detail(33).

* valve A: inlet valve, delivers unfiltered water to the filter box
* valve B: float-controlled regulating valve to provide constant head
* valve C: drain-off valve, supernatant water
* valve D: backfilling valve
* valve E: drain off valve, filter box
* valve F: flow regulating valve
* valves G and H: drain off valves, weir chamber
* valve J: outlet valve, delivers filtered water to clear water reservoir
* valve K: drain off valve, for drawing filtered water immediately following a new filtration cycle(i.e., the initial filtered water is wasted until Schumutzdecke is formed).

It should be pointed out, however, that, in practice, the number of valves used is much less to simplify the operation and to reduce costs. This is usually accomplished by controling several desired functions through the operation of a single valve (e.g. backfilling and

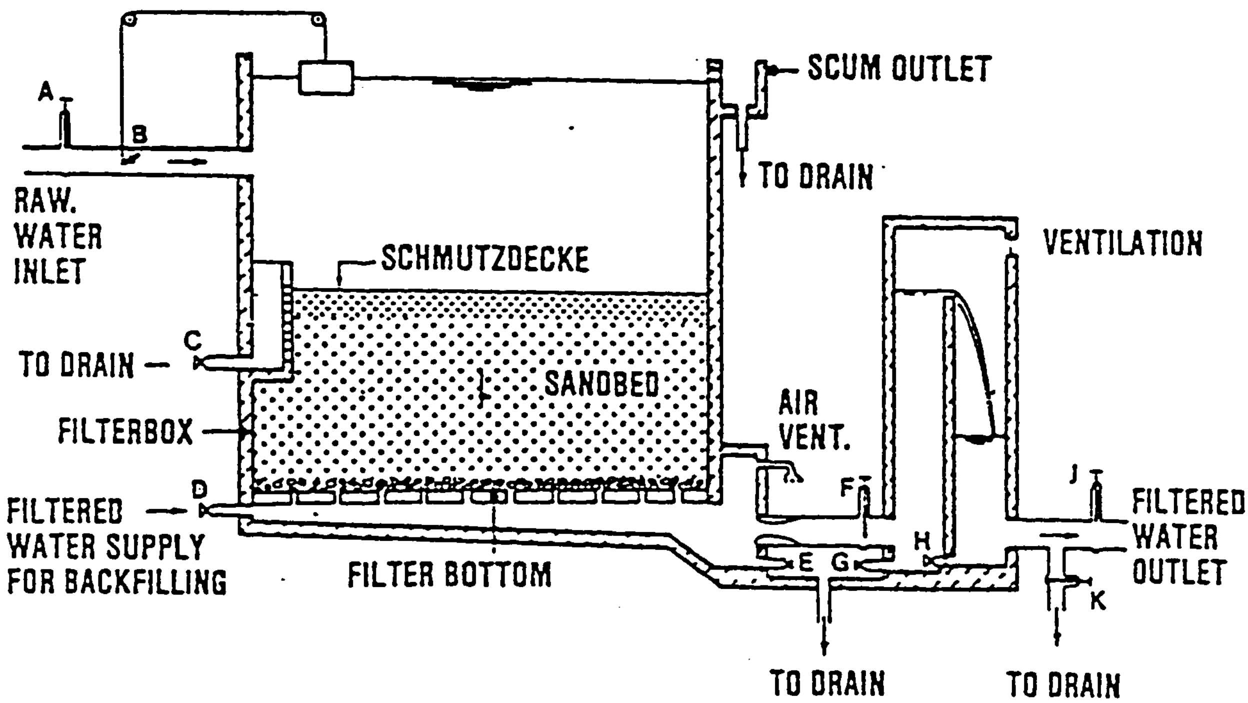

Figure 2.5: Control Valves in a Slow Sand Filter (33)

draining can be done through one valve).

2.2.2 The Purification Mechanisms

The purification process encountered through the slow sand filters is still not perfectly understood, eventhough it is the oldest water treatment process. However, the following mechanisms are expected to take place in each operational cycle which lead to effective suspended solids and bacterial removals.

Sedimentation and Straining: During the first few days of the filter operation cycle, the main mechanism of purification is sedimentation and straining. The top water reservoir acts as a highly efficient sedimentation tank since the surface loading is very low. (The maximum loading used in practice is 0.4 m/hr or 9.6 m/day which is much lower than the typical rates of 20-40 m/day used for the design of sedimentation tanks(21).) Relatively large suspended matter settle on the surface of the sand bed while the smaller suspended matter is expected to be removed by straining on the top few millimeters of sand bed. Finally, Schmutz-decke, once formed will enable the removal of even smaller particles(8,11,14,33).

It should be pointed out that the top water reservoir is rich in silt, humus and debris. Such an environment is ideal for the development of various phyto- and zoobenthos. Whenever the incoming water provides nutrients, such as phosphates and nitrates, the reservoir tends to sustain a diverse phyto- and zooplankton. Shallow depths, and thus high temperatures at the sand/water interface, results in the development of phytoplankton and subsequently zooplankton(18,41). Along these lines Hutchinson(15) reported presence of algae alternating with **Daphnia** (Crustacea) and **Brachionus** (Rotifers) in such shallow ponds. This phenomenon of succession of organisms is usually referred to as "Substantial Succession". In very simple terms "Substantial Succession" refers to a prey-predator relationship where population of two different species of organisms becomes dominant in succession due to competetion for existence(10).

Chemical and Bacteriological Action: As the Schmutzdecke thickens, it will usually contain alluvial mud, organic substances, bacteria, threadlike algae and numerous other forms of aquatic life such as plankton, diatoms, protozoa, rotifers, fungi and actinomycetes(8,11,14,33). When the water passes through this layer nearly all suspended matter and bacteria are removed. Some of the coloring matter and organic matter are also removed through this layer. Usually, however the amount of organic matter will not be sufficient to support the bacterial population in the Schmutzdecke, which will in turn, lead to die-off of bacteria. Consequently, some of the aquatic organisms feeding upon bacteria will also be affected. As a result, some additional organic matter will be available from the dead organisms which will serve as the food for bacteria at lower depths. Deeper in the filter bed, the food for bacteria, in any form, becomes scarcer and scarcer due to the biochemical decomposition of organic matter and this, in itself, will lead to die-off of the bacteria at lower depths. In other words, the original degradable organic matter present in inlet water will be gradually broken down and finally discharged with the effluent as inorganic compounds such as carbon dioxide, nitrates, sulfates and phosphates(8,14)

2.2.3 Effects of Algae

Algae are unicellular or multicellular photolithotrophic organisms, (i.e., they derive their energy from sunlight and use inorganic compounds as their carbon source), belonging to the phytoplankton group. They grow in surface waters as a result of the presence of certain nutrients (nitrates and phosphates, in particular). There are several forms of algae and that can be present in water in a very high concentration (as high as 35,000 forms per milliliter (8)). They are usually green, and the most common species are **Chlamydomonas, Scenedesmus, Navicula, Nitzchia** and **Melosira** (11,14,34).

The major adverse effects of algae on the operation and efficiency of a slow sand filter are:

- increase in head loss,
- difficulties associated with filter cleaning, and
- increase in concentration of soluble organics due to their death and decay.

Other changes would also occur as a result of the presence of algae in water. For example, the pH would increase considerably (up to pH 10, or even higher). This is due to the photosynthetic activity of algae. Inorganic carbon sources like CO_2, bicarbonate, and carbonate are used for anabolic processes and, as a result, the natural acid neutralizing capacity is reduced as hydroxyl ions are produced(8,11).

Another important change in the water due to algae is related to the dissolved oxygen content. During the daytime, as a result of photosynthesis, oxygen will be produced in accordance with the following photosynthesis equation (8,11,14,33):

$$CO_2 + 2H_2O + \text{sunlight} \dashrightarrow (CH_2O) + O_2 + H_2O$$

The dissolved oxygen content could rise to as much as three times the theoretical saturation level during the daytime (14). However, the reverse reaction will occur during the night (i.e., consumption of O_2 and production of CO_2). Eventhough the rate of oxygen consumption at the night will be only 10 to 15 % of the rate of oxygen production during the day, the water reservoir may be anoxic (i.e., low dissolved oxygen levels) during the night if the water has a high algal concentration. Such a condition will enhance the anaerobic activities and in turn cause taste and odor problems(8).

Incidentally, algal growth in filters is not totally disadvantageous. At moderate concentrations, they help in building up the Schmutzdecke. They also perform a useful service in supplying oxygen to water. At high concentrations, however, they should be controlled physically or chemically. Physical controls include covering the filter and the feed reservoir to prevent the exposure of water to direct sunlight or harvesting the algal blooms from water surface periodically. Chemical controls include prechlorination, preozonation, or addition of copper sulfate to the water(8,32).

One might think that prechlorination would be disadvantegous to slow sand filtration since the main functioning of the filter depends on the Schmutzdecke, which contains several types of microorganisms. However, studies showed that even prechlorination resulting in total chlorine residuals of 8.8 mg/l, extended the operational run of the slow filters, without harmful effects on the treatment process. This is probably due to the prevention of algal growth in the supernatant reservoir(2,16,40).

2.2.4 Head Loss Development

Mathematical representation of the head loss buildup due to clogging during the filtration is very difficult, if not impossible. This is mainly because porosity, a major variable, changes with different degrees of clogging during the operation. Nevertheless, several expressions have been proposed for the calculation of initial head loss (i.e., clean bed head loss) such as Carman-Kozeny, Fair and Hatch, Rose, and Hazen equations (21,39). As an example the Fair and Hatch equation is given below:

$$h/L = \frac{36\ k\ v\ (1 - n)^2\ V}{g\ n^3\ w^2} \sum \frac{p_i}{d_i^2}$$

where h/L = head loss per unit depth of filter bed, m/m

k = empirical constant equal to 5.0, dimensionless

v = kinematic viscosity, m^2/s

n = porosity, dimensionless

V = filtration velocity, m/s

g = gravitational acceleration, m/s^2

w = sphericity of grains (0.8 for rounded and 0.7 for angular) ,

p_i = fraction of total weight of filter grains in layer i, dimensionless

d_i = geometric mean diameter of grains in layer i, m

2.2.5 Performance

Unfortunately, the literature published on slow sand filtration, in general, is limited. Moreover, most of the available literature is about their application on potable water. Excellent performance of slow sand filters has been shown in many experimental and pilot-plant models as well as full-scale water treatment plants, especially, in terms of suspended solids and microbial contamination. Along these lines, the reported performance of slow sand filters regarding virus removal, as given in Table 2.2, is worth noting(12). Poynter and Slade (24) observed that polioviruses were removed with an efficiency similar to and in all cases slightly higher than that of coliform bacteria. Such an observation implies that routine bacteriological tests can be indicative of virus removal. This is an important conclusion given the fact that assessment of viral quality of waters is an expensive process, requiring highly specialized personnel.

Bellamy et al(3) conducted pilot-plant studies to determine the efficiency of slow sand filters in removing Giardia cysts in particular. They reported that slow sand filtration removed virtually 100 percent of

Table 2.2: Removal of Viruses by Water Treatment Processes (12,24)

Unit Process	Percent Removal
Slow sand filtration	99.8-99.9999
Diatomaceous earth filtration	>99.95
Direct filtration	90-99
Conventional treatment	99

Giardia cysts, 99 percent of total coliform bacteria, 96 percent of standard plate count bacteria, and 98 percent of suspended solids. Their findings were confirmed by Hansen (12) who reported the removal efficiencies of Giardia Lamblia by several filtration methods as shown in Table 2.3 . In a follow-up study, Bellamy et al(4) investigated the influence of selected process variables on slow sand filtration. Their findings are summarized below:

Temperature: The slow sand filters removal efficiency decreased with decreasing the ambient temperature in terms of total coliform bacteria and standard plate count bacteria. However, in terms of Giardia cysts removal, the filtration efficiency was insensitive to temperature variations.

Sand Bed Depth: It was found that the minimum bed depth can reach 48 cm without significant effect on the bacteriological quality of filter water.

Sand Size: An insignificant decrease was observed in total coliform bacteria removal efficiency when the effective size of the sand bed was increased. On the other hand, Giardia cysts removal were again insensitive to sand size variations.

Table 2.3: Removal Efficiencies of Giardia Lamblia by Different Filtration Processes (12)

Unit Process	Percent Removal
Rapid filtration with coagulation, sedimentation	98.8-99.9
Direct filtration with	
- coagulation	95.9-99.9
- no coagulation	10-70
Diatomaceous earth filtration	>99.9
Slow sand filtration	100

Hydraulic Loading Rate: There was an apparent decrease in the removal efficiencies of total coliform bacteria, standard plate count bacteria, and turbidity with an increase in the hydraulic loading. However, it is reported that within the range studied the difference was not substantial.

The literature on the application of slow sand filter to wastewaters as a tertiary treatment step is very limited. Earlier studies (17,25,38) showed 35-55 and 60-65 % removal of BOD and SS, respectively, from secondary effluents through slow sand filtration. These results were below the expected results in view of the excellent performance of slow sand filters with potable waters. In a comprehensive research about slow sand filtration (32) using pilot-plant filters, the performance of the slow sand filters was evaluated for the treatment of lake water, artificially contaminated by adding sewage. It was concluded that the filters gave a "satisfactory" performance until the BOD and COD values of contaminated raw water exceeded 5 and 20 mg/l, respectively.

In a recent laboratory study using 14 cm (in diameter) and 2.65 m (in height) filter unit, Ellis (7) reported that consistent removals of at least 90% of SS, more than 65% of BOD and over 95% of coliform organisms were observed from the secondary effluent of an operational trickling filter plant. The average length of the operational run was 20 days at 0.14 m/hr while it was 13 days at 7.0 m/d 0.29 m/hr. Similar, but slightly inferior results are reported when the secondary effluent was taken from an operational activated sludge treatment plant. Results of experimentation using two different sand sizes are also reported. It was observed that the finer sand (ES = 0.3 mm) was slightly better, in terms of contaminant removal, than the coarser sand (ES = 0.6 mm), however, the latter yielded longer operational cycles, as expected.

Another important observation made by Ellis (7) was the fact that denitrification process (as evidenced by a decrease in nitrate concentration) was taking place during filtration, contrary to expectations. He initially thought that this was due to the low dissolved oxygen content of the influent (about 1.5 mg/l). However, he later found out this was not the reason when he observed that denitrification continued at "unreduced rate" even when the influent dissolved oxygen was increased to 8 mg/l via diffused aeration. Scutt(30) raised an interesting point on this subject. He claims that because Ellis's observation is based only on nitrate concentration, the possibility of nitrification also taking place should not be eliminated. In other words, he states that it is possible to have nitrification taking place in the upper aerobic layers of the sand bed followed by denitrification due to absence of oxygen in the lower layers.

Finally, although the information presented earlier in this chapter summarizes the nature of slow sand filtration process, it must be emphasized that there is no generalized approach for the design of full-scale filters. This is mainly because of the variation of the influent characteristics which in turn effects the filter performance. Hence, the best way to ensure appropriate performance of a filtration unit is to conduct pilot plant studies.

Chapter 3

EXPERIMENTAL WORK

3.1 EXPERIMENTAL SET-UP

The pilot-scale filter unit was located within the boundaries of the KFUPM Agricultural Research Farm. Secondary effluent is available in the farm through a pipeline from the nearby North ARAMCO Wastewater Treatment Plant (NAWTP). The NAWTP has a design capacity of 30,000 cu.m.day and is currently serving ARAMCO housing in addition to KFUPM. It is an extended aeration plant operating satisfactorily yielding a high quality secondary effluent.(Plant records in the past year (1988) show that an average BOD and SS removals exceeded 97% (1).) The effluent is stored in a holding pond (135 x 65 x 4 m) from which it is pumped, following chlorination, to a spray field located 5 km away. Presently, limited reuse of the effluent is being practiced in the form of landscape irrigation within the NAWTP premises and a small area within the KFUPM campus.

__Filter Box and Auxiliaries__: The filter unit was constructed at the Central Research Workshop at KFUPM. It was constructed using three 2 mm galvanized iron sheets. Each sheet was welded to form a hollow cylinder with an inside diameter of 100 cm. The cylinders are connected to each other with angles using bolts and nuts. A rubber gasket ring is placed between the angles to avoid leakage. U-tube manometers and sampling ports are provided on the middle cylinder. A fine wire mesh was placed at these ports openings from inside, to prevent clogging by sand particles. An overflow weir was mounted to the top cylinder for achieving a uniform and steady inflow. A float switch unit was also assembled to the top cylinder to turn on/off the inlet pump, so as to keep a constant water level in the unit. Outlet and drain valves were provided at appropriate locations. A detailed description of the filter box and auxilaries are shown in Figure 3.1 .

Installation: A reinforced concrete slab of 15 cm thickness was constructed on the ground to serve as a leveled and rigid base for the filter unit. Then,the first cylinder (100 cm in height) was installed using a portable crane.The underdrain system consisting of open-joint standard bricks (Figure 2.4) was adopted in this study. The bricks were laid on the cylinder bottom in a grid with 1 cm openings between adjacent

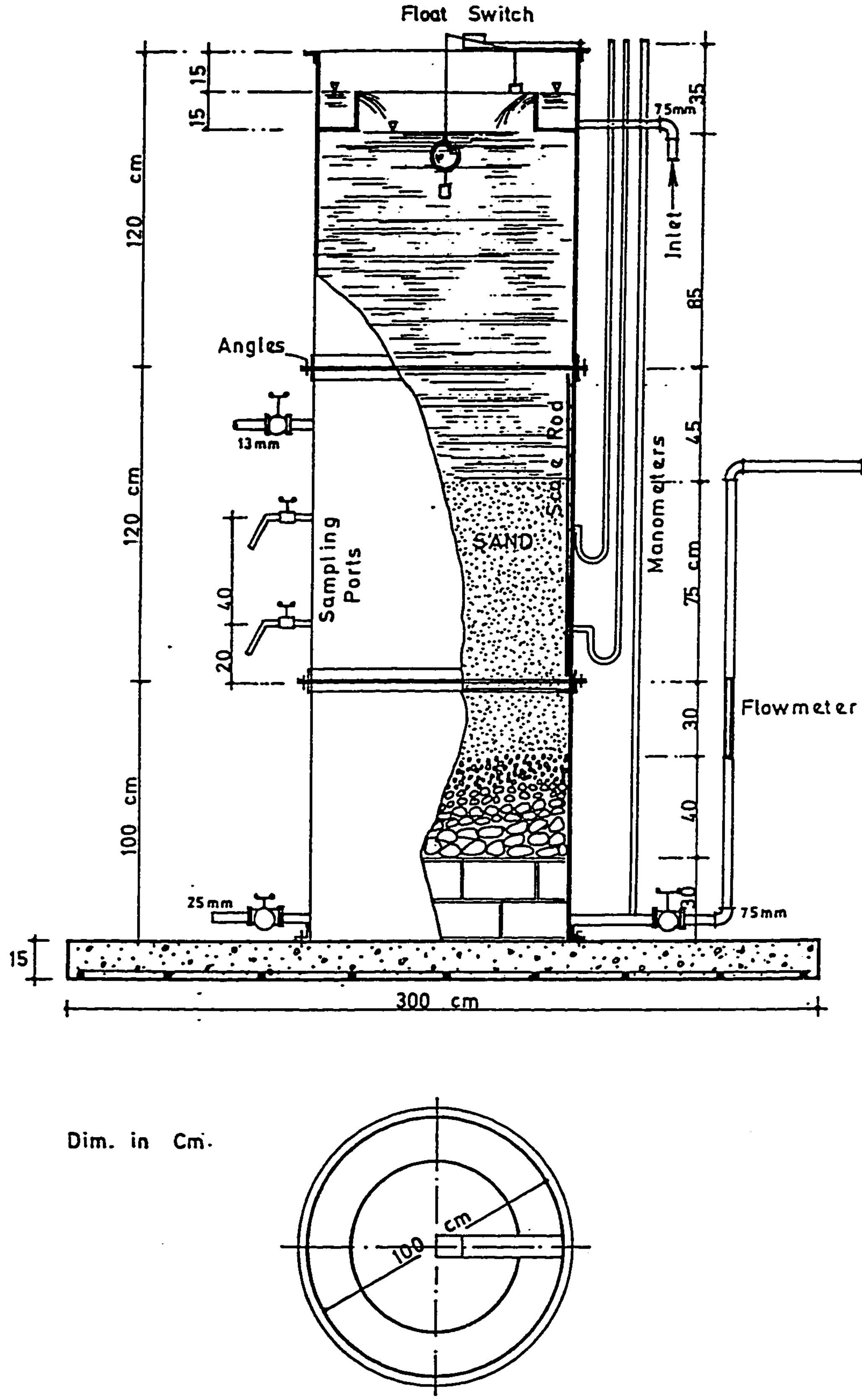

FIGURE 3.1 PILOT FILTER UNIT

blocks. Similarly,the supporting gravel was washed and placed in four layers. The depth and size distribution of each layer is given in Table 3.1 . This was followed by washing and placing the sand up to the rim of the first cylinder. The sand used was obtained locally, and it was sieved to obtain a media of recommended size and uniformity (i.e., ES = 0.23 mm and UC = 1.9). The gradation curve for the sand used is given in Figure 3.2 . The second cylinder (120 cm in height) was then mounted on top of the first cylinder and fixed with bolts and nuts. It was filled with washed sand up to the initial sand depth level (105 cm). Then, the top cylinder (120 cm in height) was mounted on top of the second cylinder. Finally, the float switch assembly was connected to the electric supply of the inflow pump and the inlet and outlet piping was completed. A summary of the depth of filter box elements are shown in Table 3.2 .

3.2 EXPERIMENTAL PROCEDURE

Characterization of Secondary Effluent: Prior to initiation of experiments, it was intended to have baseline data for the secondary effluent that was going to be used in the study. During the installation of the

Table 3.1: Depth and Size of Gravel Layers

Layer	Depth, cm	Size, mm
Bottom	20	12.5-25.0
Second	10	5.0-12.5
Third	5	2.0-4.0
Top	5	0.3-1.5

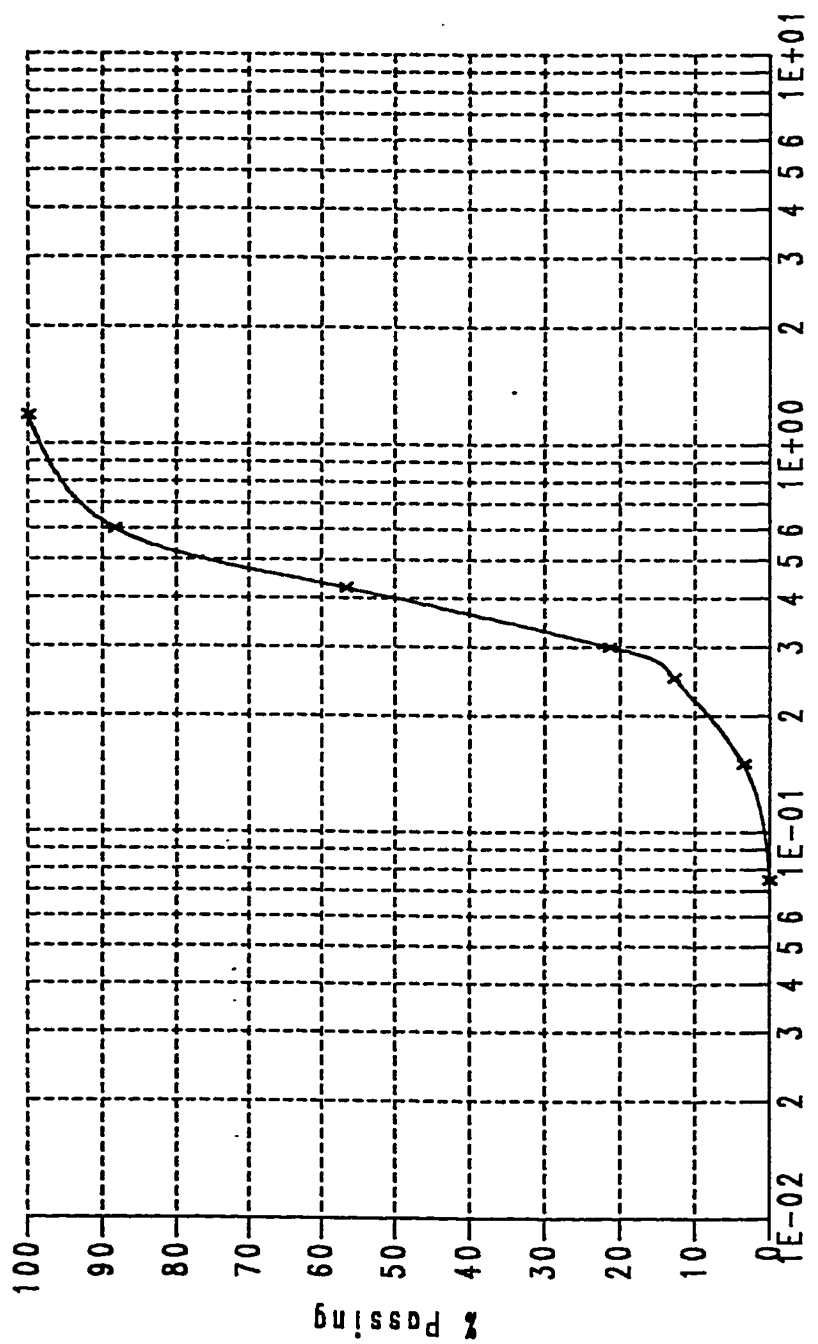

Figure 3.2: Gradation Curve for the Sand Used

Table 3.2: Depth of Filter Box Elements

Element	Selected, cm	Recommended, cm (14,29)
Freeboard	20	20
Supernatant water	145	100-150
Sand (initial)	105	100-120
Supporting gravel	40	10-50
Underdrains	30	20-30
Total	340	300-400

filter unit, samples were taken from NAWTP and analyzed for basic parameters.

System Preparation: The filter was first operated using clean water mainly to check for leakage and proper operation of sampling ports and valves. This was followed by checking the inflow arrangements to the system. The secondary effluent from the NAWTP was first directed to a storage reservoir (8 x 8 x 1.5m). The feed from the reservoir was done by using a submersible pump.Two control valves were connected to the pump line for controlling the flow rate.

Filter Ripening - Initial Runs: When the filter was ready it was operated at a flow rate of 3 L/min (corresponding to a hydraulic loading (Q/A) of 0.24 m/hr for two runs. This was followed by two more runs at 1.3 L/min (corresponding to Q/A of 0.1 m/hr). These four runs, which will be referred to as *Initial Runs* from hereon, were conducted mainly for ripening of the sand filter (i.e. maturation of the sand bed). As reported in the literature (7,8,11,14,33) a stable filtrate quality can be achieved only after the filter bed has biologically matured. Ellis(8) states that absence of ammonia in the filter effluent would indicate a mature filter. Throughout the *Initial Runs* samples were taken from the inlet, outlet, and sporadically from the sampling ports and tested for selected parameters. In addition, the clean bed (initial) head loss and head loss build-up were recorded.

Evaluation of System Performance - Routine Runs: Following all the above preparatory steps experiments were initiated in order to evaluate the system performance. The unit was operated continuously in a constant-head, constant-rate mode for a predetermined hydraulic loading (which simply translates into a specific discharge as the area of the filter is constant). Samples were collected daily from the inlet, outlet, and occasionally from the sampling ports. At the same time manometers readings were recorded to observe the accumulation of head loss. The samples were analyzed in accordance with the procedures given in the Standard Methods (34) for several parameters except algal concentration which was determined by the microtransect method descriped by Edmondson(6). That is, a defined microvolume of homogenous sample was uniformly spread on a microslide and covered with coverslip. The entire area of the sample is then segmented in terms of magnification of the microscope and the population was summed up by enumeration. Table 3.3 shows the parameters investigated, the analytical procedure used, and the frequency of analyses.

The desired filtration rate was achieved by the manual adjustment of the effluent valve. As filtration progressed, the resistance to flow or head loss was increasing due to clogging. Consequently, the filtration rate was decreased because the available head above the sand surface is fixed (i.e., constant-head). At this point the effluent valve was manually opened further until the desired flow rate is established. In other words, the head loss due to the valve was decreased (by opening it further) by an amount equal to the head loss build-up due to clogging. This operation was continued until the outlet valve was wide open. (Once the outlet valve is wide open it means that the head loss due to the valve has reached its minimum value and thus it cannot be decreased any further.) In this case the run was terminated by discontinuing the inflow. The filter was drained to a level below the sand bed surface by 10 to 20 cm. Then, the top 2 - 4 cm of the sand bed (i.e., Schmutzdecke) was manually scraped using a long handle scraper. The filter was then refilled from the bottom with clean water

Table 3.3: Parameter Evaluation Schedule

Parameter	Analytical Procedure (34)	Frequency
Total BOD	Standard (5-day)	Daily
Total COD	Dichromate Reflux Method	Every other day
Total SS	Standard	Daily
Turbidity	Hach Turbiditimeter, Model 2100	Daily
Total Coliforms	MPN Method	Every other day
pH	Corning pH Meter, Model 10	Daily
Alkalinity	Standard	Twice a week
DO	Azide Modification	Daily
Temperature	Standard	Daily
Conductivity	Hach Conductivitimeter	Weekly
Total Solids	Standard	Random
Residual Chlorine	DPD ferrous titrimetric method	Twice a week
Surfactants	Methylene Blue Method	Random
Color	Spectrophotometer	Random
TKN:		
Ammonia	Preliminary Distillation Step	Occasionally
TON	Macro-Kjeldahl Method	Occasionally
Nitrite and Nitrate	Cadmium Reduction Method	Occasionally
Phosphorus	Ascorbic Acid Method	Occasionally
Sulfate	Turbidimetric Method	Occasionally
Chloride	Mercuric Nitrate Method	Occasionally
Algae and Rotifers	Edmondson's Method (6)	Occasionally

to a level of approximately 50 cm above the sand bed at which the inflow pump was restarted. This was done to avoid any possible disturbances of the sand bed. Finally, the desired filtration rate was adjusted by the effluent valve and the filter was ready for the next operational cycle.

Overall 9 experimental runs were done covering a period of 7 months. It should be pointed out that experiments were carried during the winter months so as to simulate the most adverse operational conditions with respect to temperature.

Chapter 4

RESULTS AND DISCUSSION

4.1 CHARACTERISTICS OF NAWTP EFFLUENT

The secondary effluent of NAWTP can be considered as a typical effluent of municipal sewage subjected to treatment by extended aeration processes. Table 4.1 summarizes the basic parameters of this effluents before and after chlorination. Clearly, the effluent satisfies the secondary effluent standards stated in Chapter 1. However, for direct reuse, tertiary treatment is still necessary from a bacteriological standpoint. In spite of chlorination, the total coliform concentration in the effluent was found to be as high as 240 MPN / 100 ml, on several occasions.

4.2 INITIAL RUNS

Four sets of experiments were carried out during this phase at two different hydraulic loadings.

Hydraulic Loading: 0.24 m/hr

The first two runs were operated at a hydraulic

Table 4.1: Characteristics of the NAWTP Effluent

Parameter	No. of samples	Unchlorinated	Chlorinated
pH	10	8.2	8.0
BOD, mg/l	10	<5.0	<5.0
SS, mg/l	10	5.0–16.0(12.0)*	6.0-14.0 (11.5)*
Total Coliform Bacteria, MPN/100ml	10	$35x10^3$ – $160x10^3$	<2 - 240
Residual Chlorine, mg/l	5	--	0.3-0.8 (0.6)*

* indicates average value

loading (HL) of 0.24 m/hr (corresponding to a flow rate of 3 L/min). The feed reservoir was half filled with fresh secondary effluent from NAWTP. Several events beyond control occurred during this period which are worth noting:

- There was a heavy growth of algae in the feed reservoir by the 2nd day of operation. It reached up to 25000 forms/ml. This is a natural phenomena of all impounded waters containing nutrients. Apparently, the high temperature within the first few days of operation (approximately 30^{0}C) and the shallow depth of the water in the feed reservoir (0.75 m) were the reasons for the high growth rate. However, on the 4th day there was a sudden drop in temperature (over 10^{0}C) which led to a massive mortality of algae. This resulted in liberating biodegradable as well as less biodegradable, but chemically oxidizable, organic matter which increased the BOD and COD values up to 12 mg/l and 90 mg/l, respectively. It should be pointed out that upon termination of the first run, the feed reservoir was emptied and refilled with fresh effluent from NAWTP. This time the reservoir was filled up to the rim (1.5 m). It was thought that increasing the depth of water would decrease the sunlight penetration which will limit the algal growth rates in the lower levels of the feed reservoir (where the submersible pump inlet is located).

- It was not possible to maintain a constant rate of filtration with the outlet arrangement used. In other words, the flow rates and manometer readings were erratic throughout the operation. Therefore, it was decided to modify the outlet system in the subsequent runs. Namely, the flowmeter was changed and the outlet elevation was lowered.

The results of the first two runs are summarized in Table 4.2 . Figure 4.1 depicts the performance of the filter with respect to the removal of total coliform bacteria. In view of Tables 4.1 and 4.2, it is observed that a deterioration of the NAWTP effluent in terms of BOD and SS occurs as it reaches to the feed reservoir. This is mainly due to the effect of algal growth in the feed reservoir. The effect of algal growth is also apparent when the DO and pH levels in the influent are noted. Supersaturation levels of DO reaching 25 mg/l and a pH of 9.4 were observed as a consequence of the process of photosynthesis. On the other hand, there was decrease in the DO content and pH

Table 4.2: Filter Performance (Runs #1 and #2, HL=0.24m/hr)

Parameter	No. of Samples	Influent		Effluent	
		Range	Mean	Range	Mean
Temperature , ^0C	18	20-30	24.5	20-30	24.5
pH	18	8.1-9.4	--	7.9-8.9	--
BOD, mg/l	18	2.5-12.0	6.9	0.5-5.0	1.9
COD, mg/l	4	50-90	68.8	20-43	32.7
DO, mg/l	18	6-25	14	3-13	7.8
SS, mg/l	18	15-43	26.3	5-20	11.0
Turbidity, NTU	18	2.5-9.0	5.6	0.4-3	1.2
Conductivity, micromhos/cm	4	5300-5500	5400	5300-5500	5400
Color, CU	4	150-230	192	10-35	22
Algae, forms/ml	4	22000-25000	23000	5900-6100	6000

Remarks (#1/ #2):

-bed depth: 105/ 100 cm
-clean bed head loss: 24/ 25 cm
-length of operation: 9/ 9 days

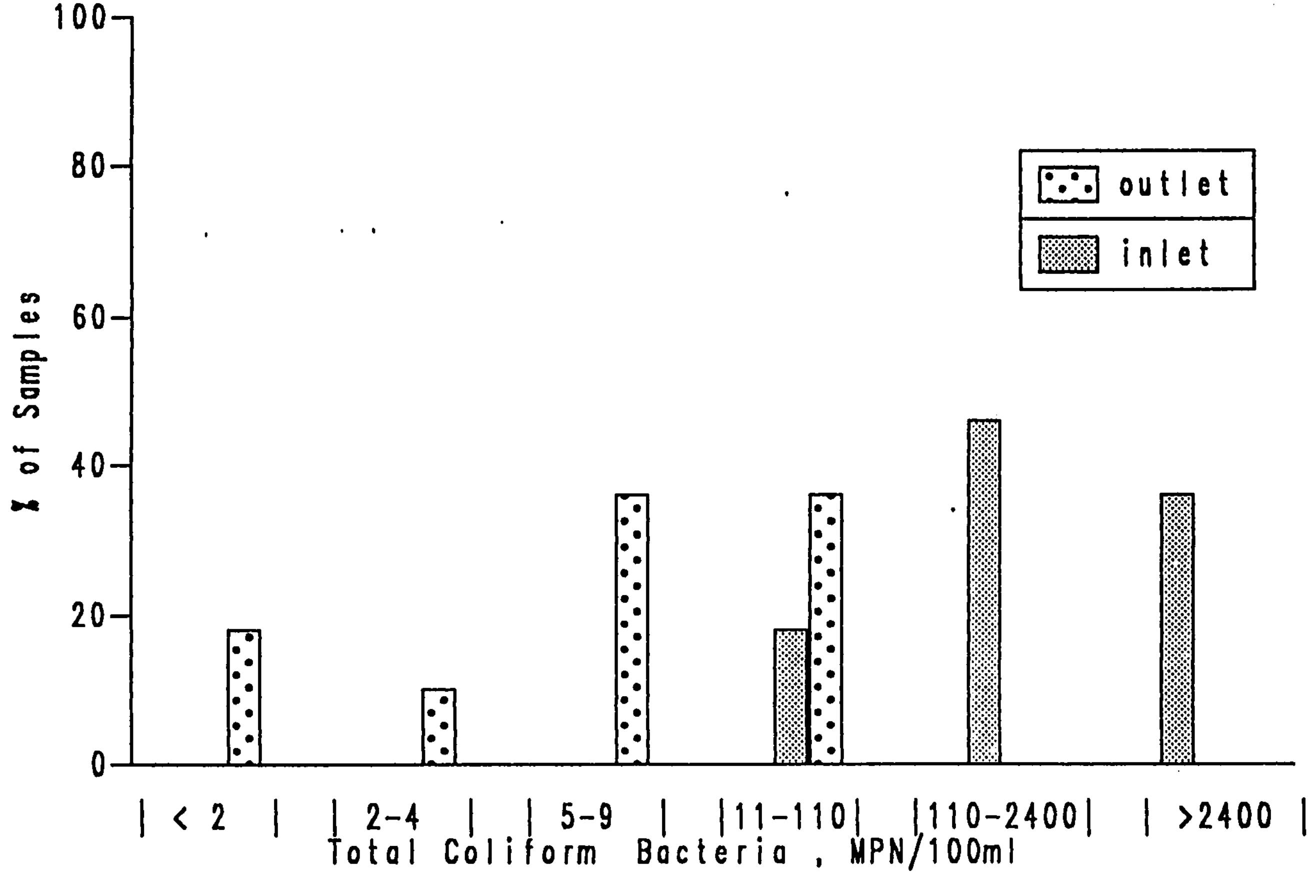

Figure 4.1: Bacteriological Performance (Runs #1 and #2 , HL= 0.24 m/hr)

in the filtrate, which is most probably due to an aerobic decomposition of organic matter occurring within the filter bed. The filter seemed quite effective regarding contaminant removal. For example, the average removal of BOD,COD,SS,turbidity, color, and algae were 73,53,58,79,88,and 74%, respectively. The bacterial count removal levels were very high as can be observed from Figure 4.1 . Incidentally, for both experiments the operational run continued for 9 days, and the clean bed headloss (about 25 cm) were well within accepted limits. In order to increase the length of operation, the next set of initial runs were carried out at a lower hydraulic loading.

Hydraulic Loading: 0.1 m/hr

Two additional experiments (Runs #3 and #4) were carried out at a hydraulic loading of 0.1 m/hr. It was intended to study the effect of delaying the cleaning operation between two successive operational cycles without draining the filter. Upon terminating Run #2, both the influent and effluent valves were closed and the system was left stagnant for three days. Then the filter was drained and cleaned and Run #3 was initiated. The results of the analyses for this set of experiment is given in Table 4.3 and Figure 4.2 . As

Table 4.3: Filter Performance (Run #3 , HL= 0.10 m/hr)

Parameter	No. of Samples	Influent		Effluent	
		Range	Mean	Range	Mean
Temperature , ^{0}C	16	20-24	22.0	20-30	24.0
pH	16	8.2-8.5	--	7.7-8.4	--
BOD, mg/l	16	2.0-5.0	2.7	1.0-2.5	1.6
COD, mg/l	6	28-72	49	22-57	38
DO, mg/l	16	3-10	7.4	1-3	1.7
SS, mg/l	16	6-20	13.5	4-10	8.8
Turbidity, NTU	16	1.0-2.5	1.5	0.4-1.4	0.6
Conductivity, micromhos/cm	4	5000-5400	5200	5000-5400	5200
Color, CU	4	20-30	25	5-15	10
Algae, forms/ml	4	195-5000	2550	35-280	133
Rotifers, #/ml	4	60-400	140	0	0

Remarks:

-bed depth: 98 cm
-clean bed head loss: 9 cm
-length of operation: 17 days

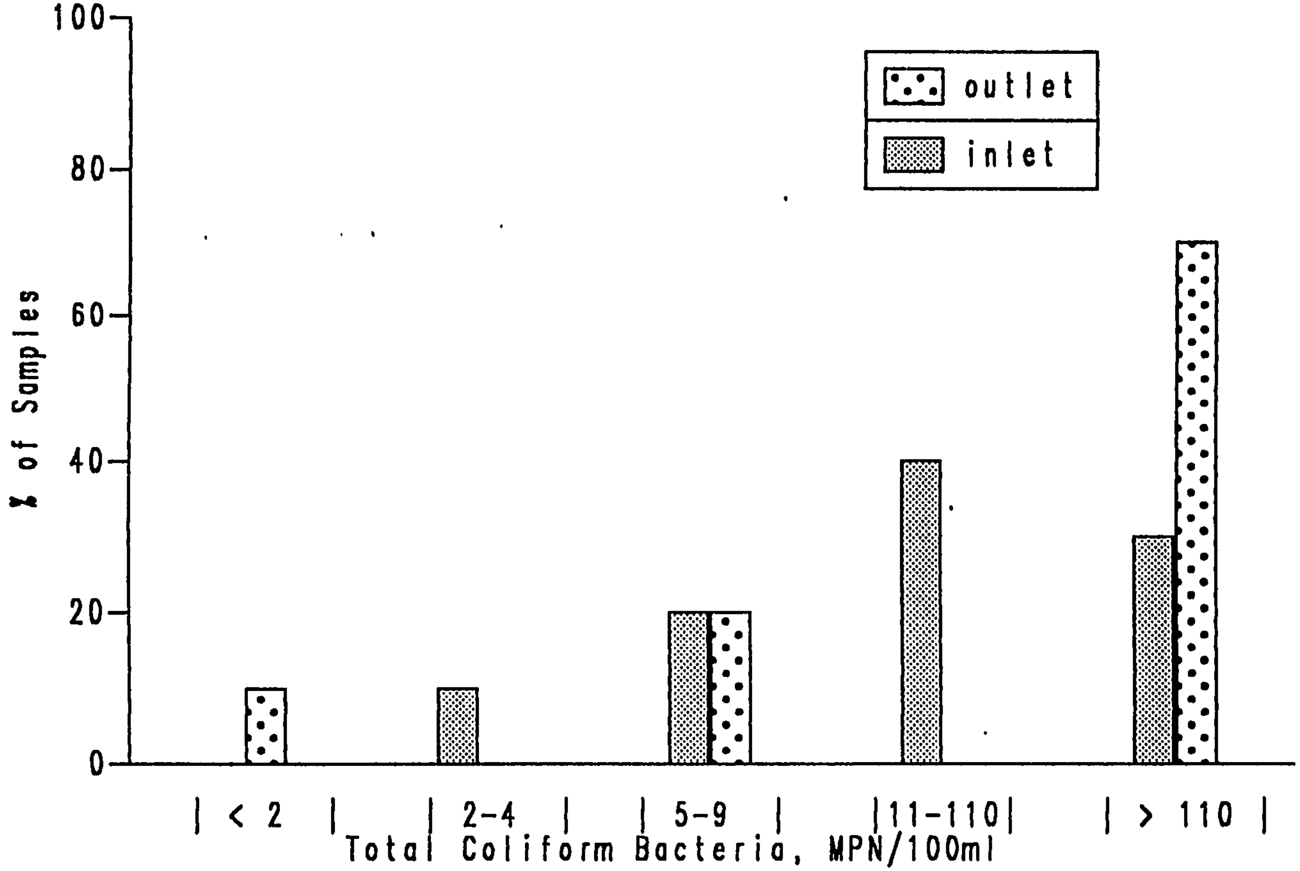

Figure 4.2: Bacteriological Performance (Run #3 , HL= 0.1m/hr)

can be seen from these, the overall effectivenes of the filter regarding contaminant removal was adversely effected. In particular, it is observed from Figure 4.2 that there was a significant deterioration of the bacteriological quality of the filtered water. Certainly, this was due to the heavy growth of bacterial population within the filter bed during the three day stagnation period. Hence, upon initiation of the operation some of these bacteria were discharged with the filter effluent. This resulted in a high total coliform concentration (over 110 MPN / 100ml) in the filtrate especially during the first few days. However, as the operational cycle progressed the total coliform concentration decreased significantly. Incidentally, during this run, the influent total coliform concentration was not high. This probably helped the relatively quick recovery of the bacteriological performance of the filter.

A significant observation during this run was the witness to "Substantial Succession" phenomena occurring in the feed reservoir. Specifically, the algae **Scenedesmus** was proceeded by the rotifer population of **Brachionus Calyeiflorus.** These rotifers constantly graze the algae, and thus, reducing the algal population in the influent. This resulted in an average algal concentration, which is almost ten times less than that of Runs #1 and #2. In view of Tables 4.2 and 4.3 it is seen that a lower algal concentration results in a higher algae removal(i.e., 95% as opposed to 74%). On the other hand, rotifers were absent from the filtrate samples in this run. It should also be pointed out that the decrease of algal population in the feed reservoir resulted in dramatic changes in the quality of the filter influent. For example, the inlet BOD, SS, and DO during this run were significantly lower than that of the Run #1 and #2. In this run, the operational cycle continued for 17 days and it was decided to conduct another experiment at the same hydraulic loading to insure the recovery of the filter from the effects of the intentional delay in cleaning after Run #2 .

Following Run #3 the filter was cleaned and operated with clean well water for one day to flush up the system. This was followed by initiating Run #4. In this run samples were also collected from the sampling ports for a week to investigate the removal of contaminants at different depths. Table 4.4 gives the average characteristics of the influent, top sampling port,

Table 4.4: Filter Performance (Run #4 , HL= 0.10 m/hr)

Parameter	NO. of Samples	Influent	Top Sampling Port	Bottom Sampling Port	Effluent
Temperature , ^0C	18	16.5	--	--	18.0
BOD, mg/l	18	2.9	--	--	0.6
COD, mg/l	6	31.8	--	--	29.4
DO, mg/l	18	12.3			8.3
	7		9.8	9.0	
SS, mg/l	18	12.2			7.8
	7		8.8	8.2	
Turbidity, NTU	18	2.0			0.4
	7		0.7	0.5	

Remarks:
-bed depth: 95 cm
-clean bed head loss: 10 cm
-length of operation: 19 days

bottom sampling port, and the effluent, while the bacteriological performance of the filter is shown in Figure 4.3 . As observed from Figure 4.3 all of the outlet samples had an MPN of less than 2 per 100ml, indicating complete recovery of the system. Another important observation was that samples from the outlet (sand depth = 95cm) was only slightly better in quality than that of the bottom sampling port (sand depth = 45cm). Some degree of contaminant removal is observed even at the top sampling port (sand depth = 5cm). This agrees well with literature (4,8,11,14,33) as it shows that purification mainly occurs in the top layers of the sand bed. The filter operation was stable throughout Run #4 which lasted 19 days.

Coupling the stable operation of the filter in the last run with the fact that the system was operational for about two months, it was assumed that the filter ripening process was complete. In summary, the *Initial Runs* were found to be very useful as they led to:

- the confirmation of the feasability of the system (i.e., effectivenes in contaminant removal),
- an estimate for the expected duration of a filtration run at a given hydraulic loading,

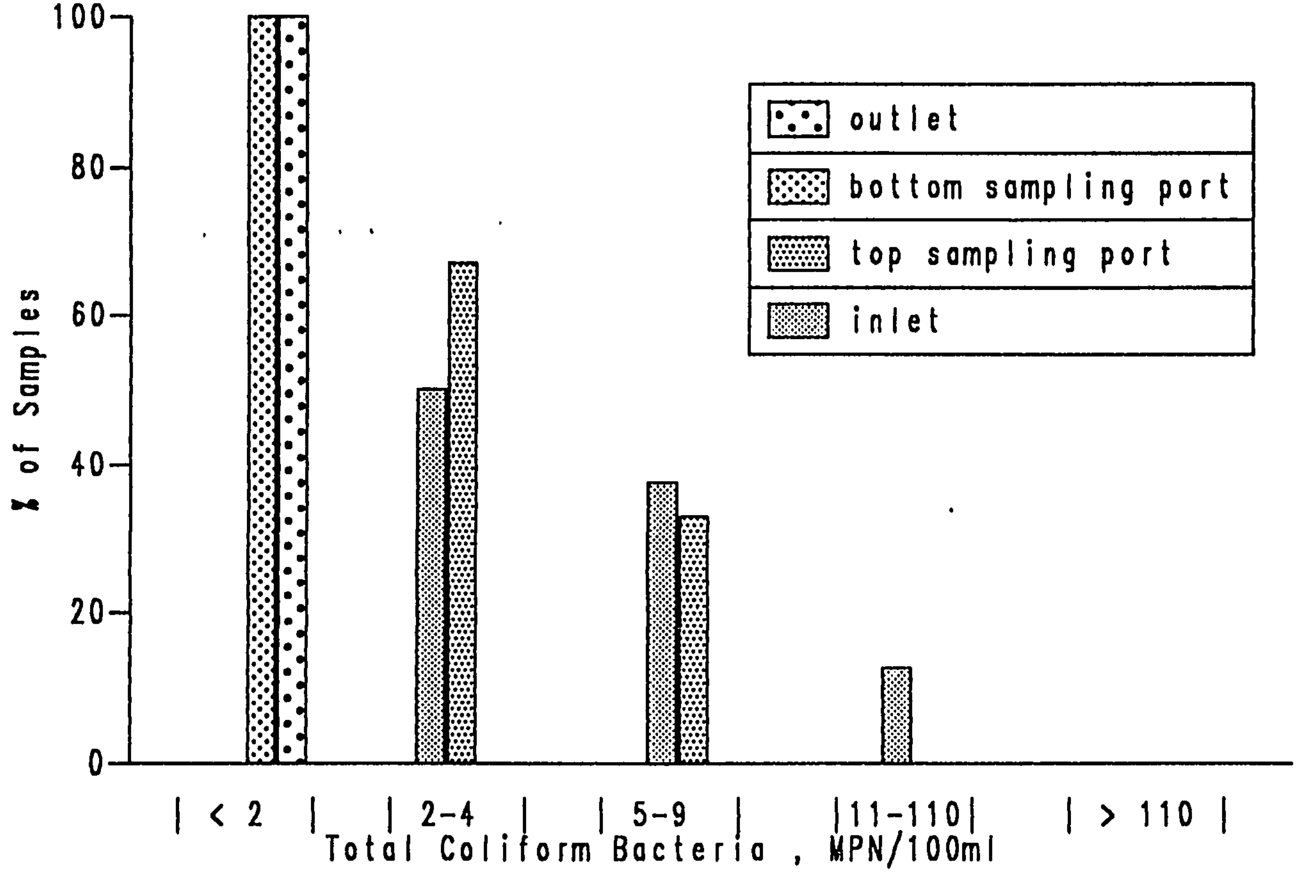

Figure 4.3: Bacteriological Performance (Run #4 , HL= 0.1 m/hr)

- minor modifications of the outlet system for proper operation,
- the observation and solution of operational problems, and
- the necessity for immediate cleaning upon termination.

4.3 ROUTINE RUNS

Upon concluding that the filter maturation was complete following Initial Runs, experimentation was carried out for evaluating the system performance. At this stage, five sets of experiments were run covering different hydraulic loadings. First, the filter was operated at 0.24 m/hr for two runs. Then, based on the results of these two runs (particularly the length of operational cycle) two lower hydraulic loadings (0.16 and 0.08 m/hr) were selected for evaluation. In view of the results of these experiments, a final run was conducted with what is thought to be the most suitable hydraulic loading.

Hydraulic Loading: 0.24 m/hr (Run #5)

At the end of Run #4 the filter was cleaned and operated at 0.24 m/hr for another operational cycle

(Run #5) which lasted 9 days. Figure 4.4 shows the head loss build-up as recorded at the three manometers throughout this run. As can be observed from Figure 4.4, most of the head loss is due to the Schmutzdecke since the head loss between the top manometer port and the outlet valve is small compared to the total head-loss. This fact is easily recognized from Figure 4.5 which is a plot of the daily variation of the head loss due to clogging(i.e., total head loss minus the clean bed head loss) per unit depth as recorded at the three manometers. A clean bed headloss of 17 cm was observed at the outlet manometer which agrees well with the value of 18.3 cm calculated by the Fair and Hatch equation (39) given in section 2.2.4 with:

$k= 5.0$; $v= 1.07 \times 10^{-6}\ m^2/s$ (for water at 17^0C)

$V= 6.67 \times 10^{-5}$ m/s ; $L= 0.92$ m ; $g= 9.81\ m/s^2$

In addition the sphericity of grains was assumed to be 0.75 and the porosity was determined as 0.37 . The latter was determined in accordance with the procedure outlined by O'Connor (22). Finally, the term $\sum\frac{p_i}{d_i^2}$ was calculated as $10.9 \times 10^6\ m^{-2}$ using Figure 3.2 .

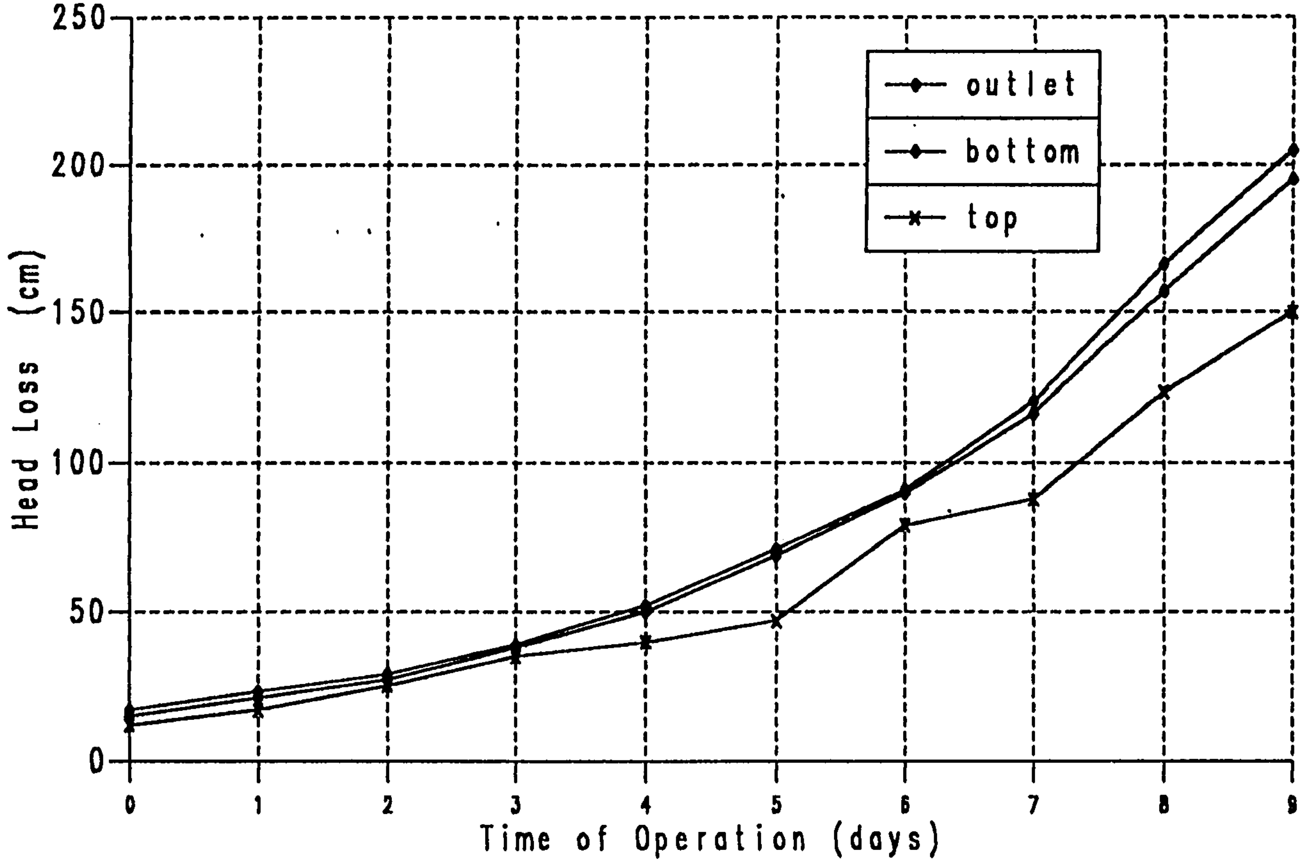

Figure 4.4: Head Loss Development Pattern (Run #5 , HL=0.24 m/hr)

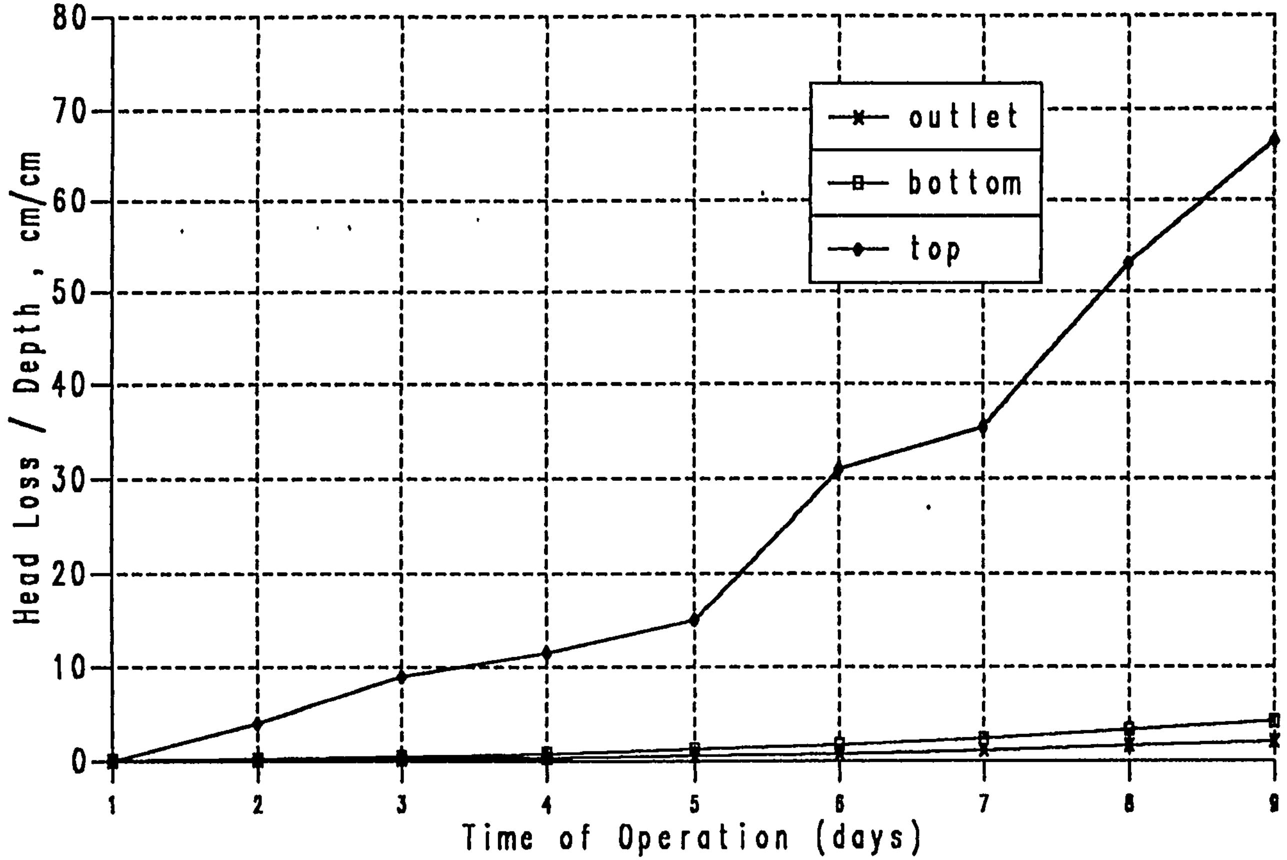

Figure 4.5: Daily Variation of Head Loss per Unit Depth (Run #5 , HL= 0.24m/hr)

Towards the end of Run #4 and consequently during this run, a moderate growth of algae was observed in the feed reservoir indicating another cycle of "Substantial Succession". Table 4.5 summarizes the filter influent and effluent characteristics of Run #5. A good performance was observed during this run. The filter removed on the average 88.5% of BOD, 57.0% of SS and 73.9% of turbidity. One might be tempted to think that the filter is not performing well since the usual removal efficiencies of SS and turbidity of slow sand filters exceed 90%, however, the relatively low values simply resulted from low influent characteristics values. The daily percent removal of BOD, SS, and turbidity throughout this run are shown in Figure 4.6, while bacteriological performance data is plotted in Figure 4.7. It can be observed from Figure 4.6 that BOD and turbidity removals were stable while an erratic pattern was observed for the SS . This may be within the limits of experimental errors which are likely in the determination of SS at low concentrations. Interestingly, the SS and turbidity data somewhat do not complement each other, this may be due to having a wide variation in particles sizes. Figure 4.7 shows that although the influent total coliform concentration was low the fil-

Table 4.5: Filter Performance (Run #5 , HL= 0.24 m/hr)

Parameter	No. of Samples	Influent		Effluent	
		Range	Mean	Range	Mean
Temperature , ^{0}C	9	16-20	17.5	16-20	18
pH	9	8.8-9.6	--	8.5-9.4	--
BOD, mg/l	9	2.0-4.5	2.6	0.1-0.6	0.3
DO, mg/l	9	11.6-13.2	12.3	8.0-9.4	8.5
SS, mg/l	9	5.0-19.2	13.5	2.0-10.0	5.8
Turbidity, NTU	9	1.8-3.3	2.3	0.4-0.7	0.6
Residual Chlorine, mg/l	4	0.3-0.4	0.35	0.2-0.3	0.25
Alkalinity,mg/l	4	110-120	114	100-115	107
Detergent, mg/l	4	0.05-0.07	0.06	0.008-0.012	0.01

Remarks:

-bed depth: 92 cm
-clean bed head loss: 17 cm
-length of operation: 9 days

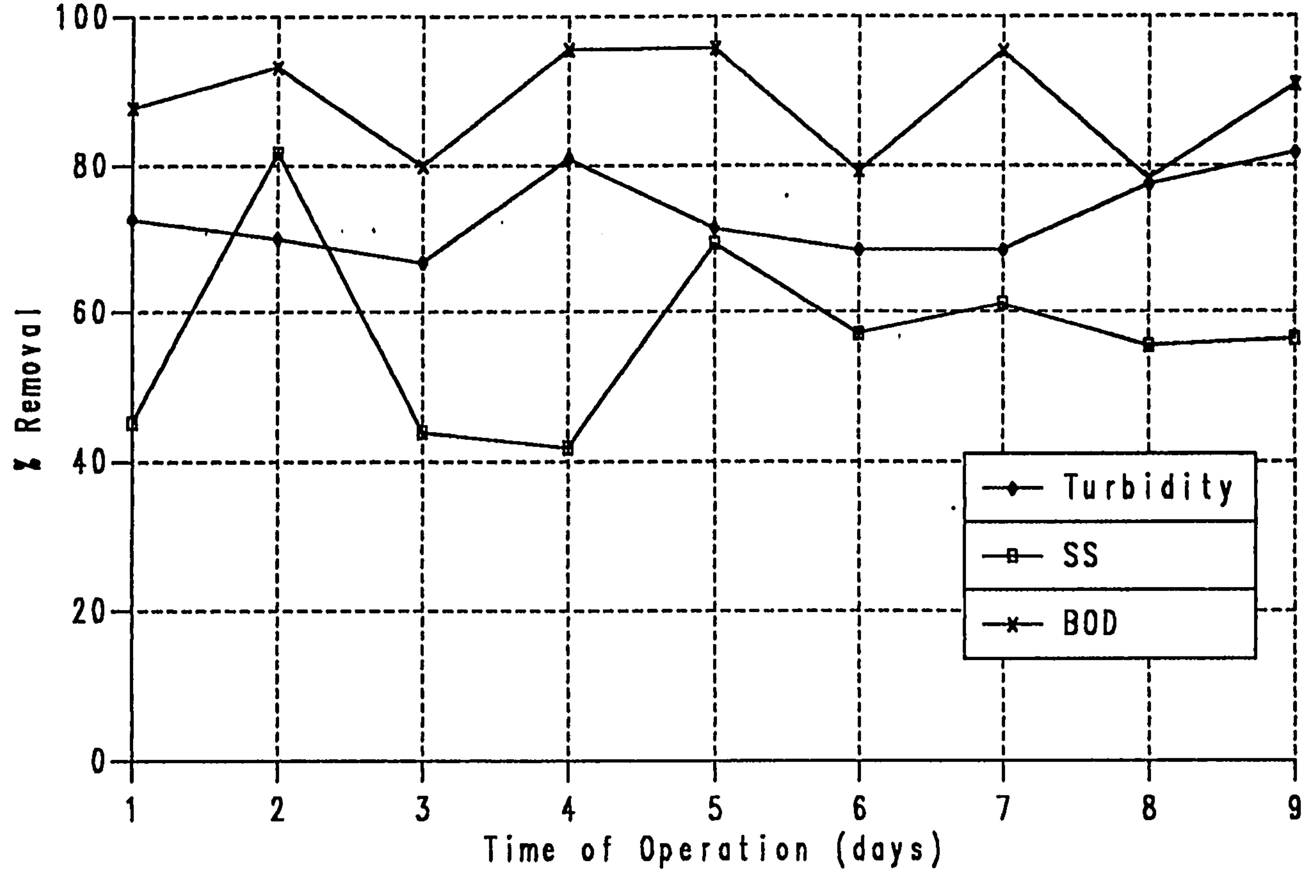

Figure 4.6: Removal of BOD, SS, and Turbidity (Run #5 , HL= 0.24 m/hr)

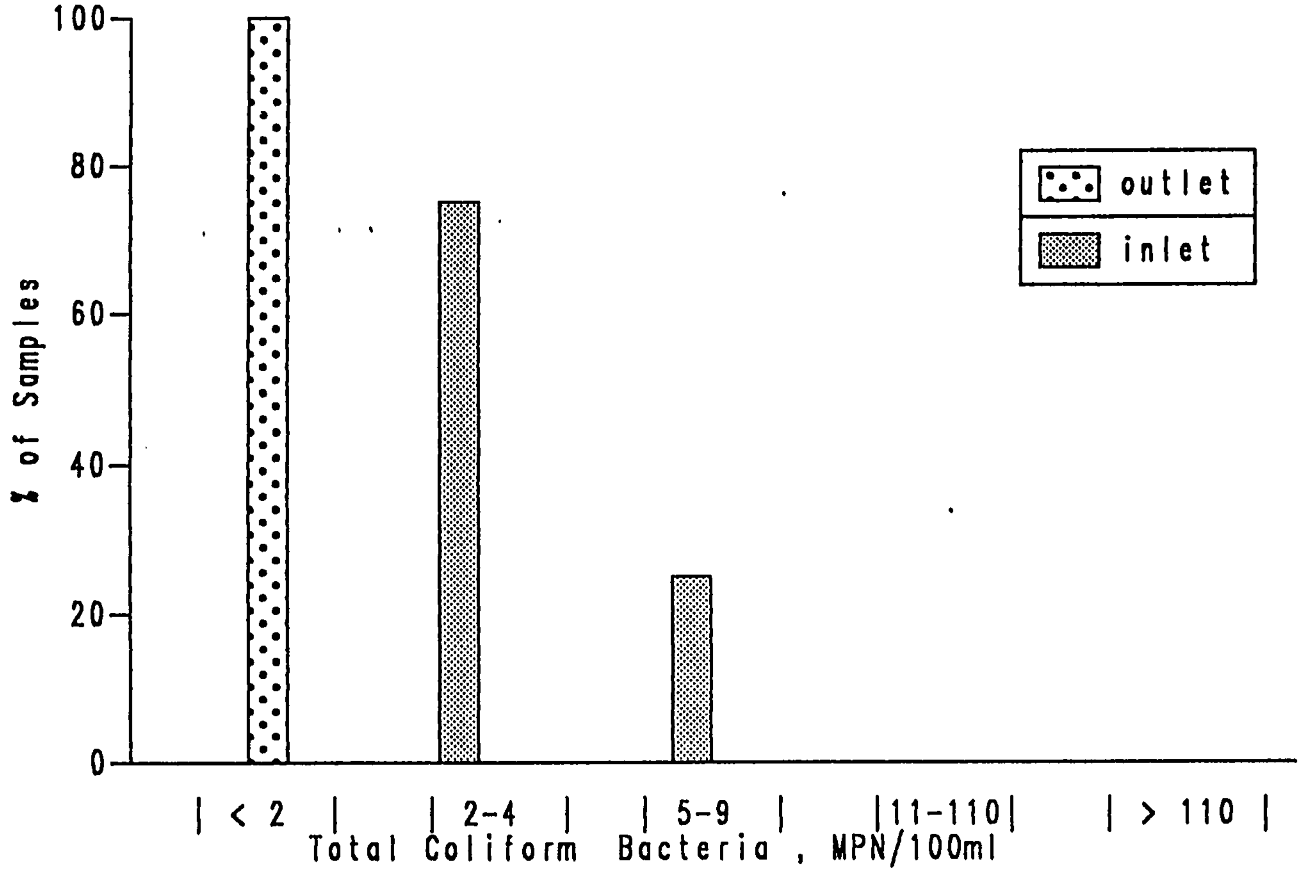

Figure 4.7: Bacteriological Performance (Run #5 , HL= 0.24 m/hr)

ter was very effective in removing them. It is also observed that both the pH and DO were reduced consistently throughout the filtration. The average detergent concentration was only 0.06 mg/l in the influent while in the effluent it was 0.01 mg/l which indicates that removal of surface active agents is taking place during slow sand filtration, possibly by adsorpton onto the media.

The major negative point of this run was the short length of the duration of operation. Evidently the presence of algae contributed to the shortening of the cycle. To verify the data on the filter performance at the hydraulic loading of 0.24 m/hr, another run was conducted at the same hydraulic loading. The head loss development pattern for this run (Run #6) is given in Figure 4.8 . Incidentally, following several scrapings the inlet of the top manometer port was above the sand surface, hence, from hereon manometer readings were made only from the bottom and outlet manometers. Table 4.6 gives the characteristics of the influent and effluent during this run, and Figure 4.9 shows the bacteriological performance of the filter. As can be seen from Table 4.6 the filter removed an average of 84.6, 50.7, 53.5 and 73.2% of BOD, COD, SS, and turbidity,

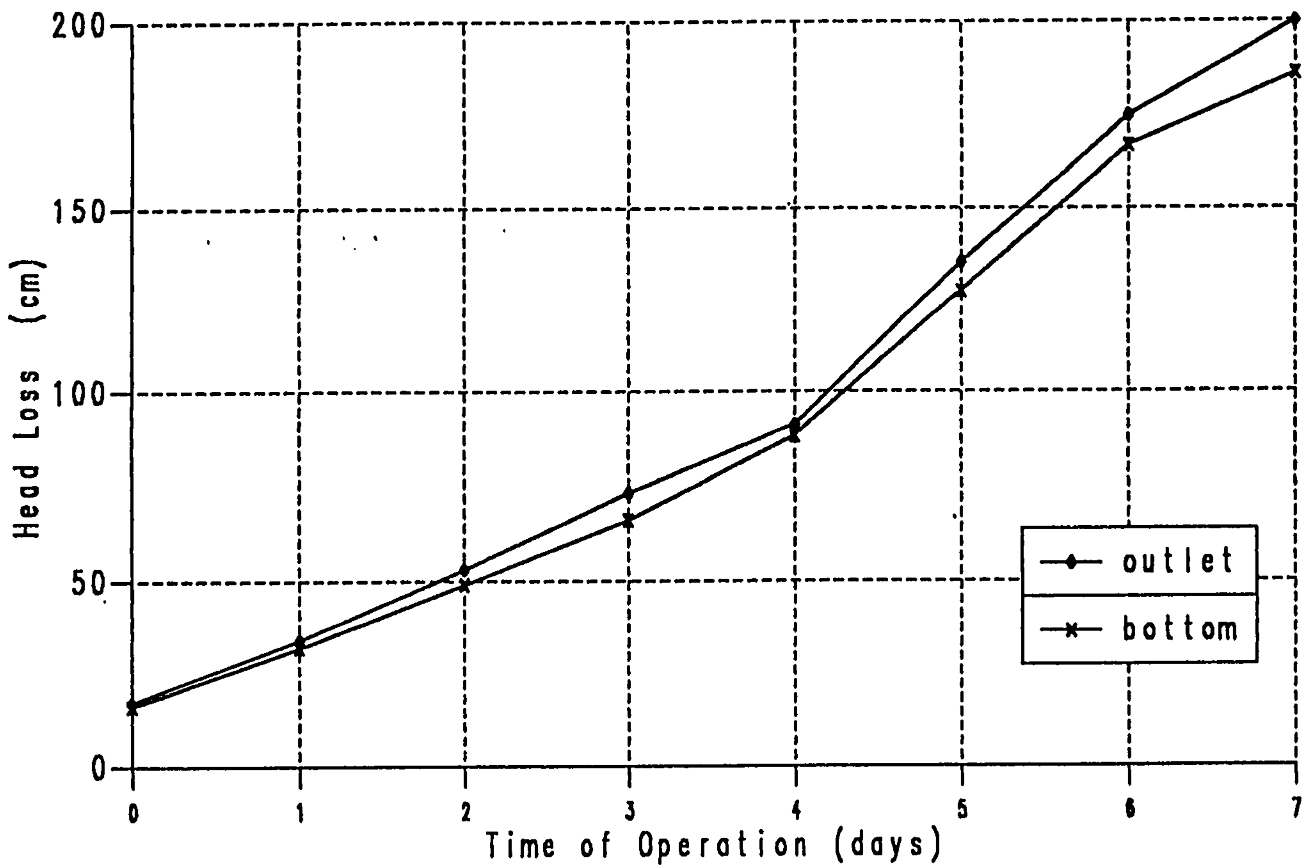

Figure 4.8: Head Loss Development Pattern (Run #6 , HL+ 0.24 m/hr)

Table 4.6: Filter Performance (Run #6 , HL = 0.24 m/hr)

Parameter	No. of Samples	Influent		Effluent	
		Range	Mean	Range	Mean
Temperature , °C	7	18-21	19	18-22	19.5
pH	7	8.8-9.1	--	8.6-8.9	--
BOD, mg/l	7	1.0-4.0	2.6	0.1-0.8	0.4
COD, mg/l	3	37-70	52.8	20-31	26
DO, mg/l	7	10.8-15.6	13.2	5.8-11.1	8.8
SS, mg/l	7	13.5-20	15.7	1.1-11.4	7.3
Turbidity, NTU	7	2.3-3.6	2.8	0.6-0.9	0.75
Residual Chlorine, mg/l	4	0.25-0.35	0.30	0.15-0.25	0.20
Conductivity micromhos/cm	3	5000-5200	5100	5000-5200	5100

Remarks:
-bed depth: 90 cm
-clean bed head loss: 17 cm
-length of operation: 7 days

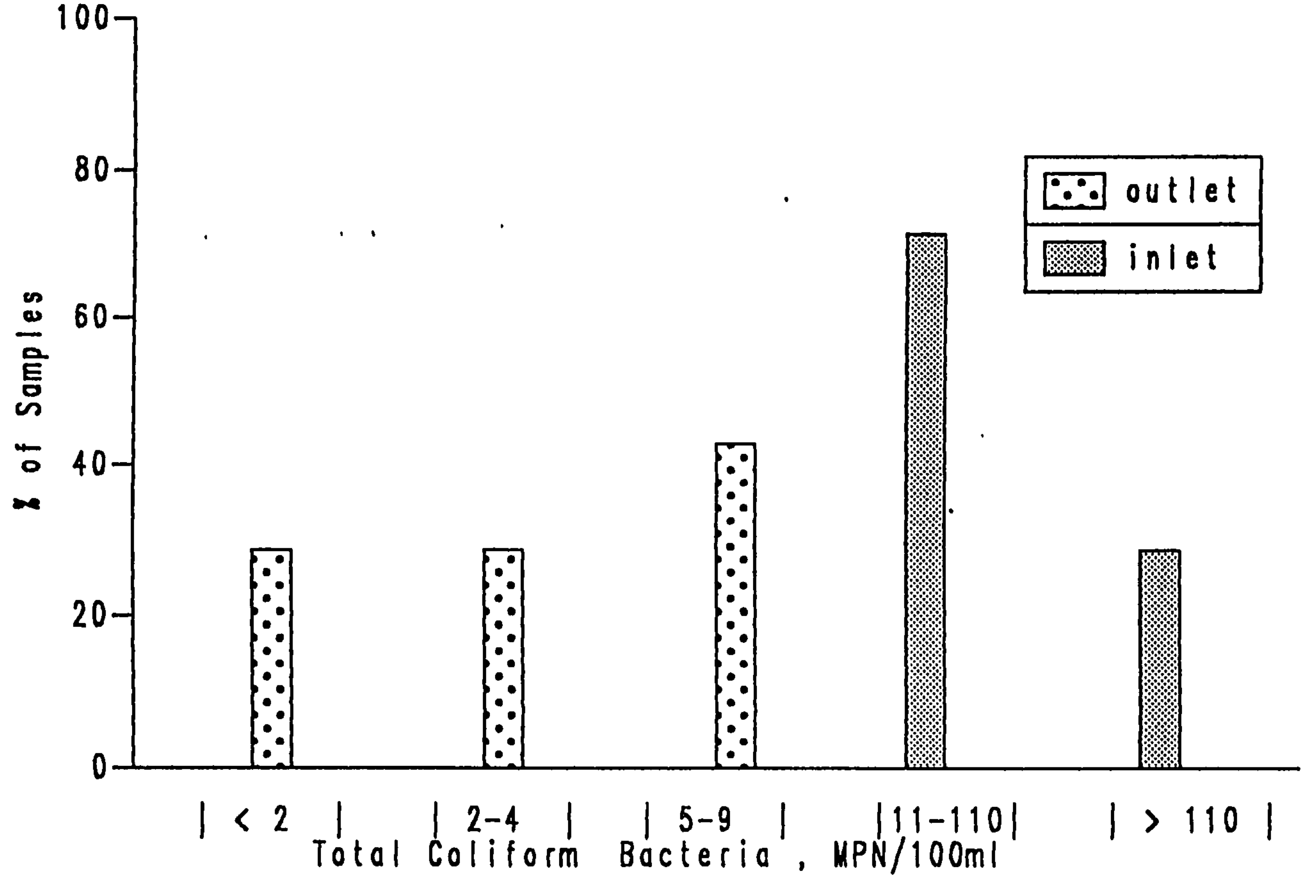

Figure 4.9: Bacteriological Performance (Run #6 , HL= 0.24 m/hr)

respectively. These were comparable but yet slightly inferior to the removals observed in the previous run. During this run the total coliform concentration was much higher than the previous run which gave a better picture of the slow sand filtration capabilities with respect to total coliform bacteria removal. The coliform test was conducted daily during this run and a removal over 95% was observed on the average. The daily removal pattern for BOD, SS, and turbidity are given in Figure 4.10. It is seen from Figure 4.10 that BOD, SS, and turbidity removals are quite stable throughout the operation.

In view of Runs #5 and #6, it is concluded that the hydraulic loading of 0.24 m/hr would yield a good performance in terms of contaminant removal provided that algal growth is controlled. However, the length of the operational cycle (7-9 days) seems to be somewhat short for a full-scale application. Consequently, two lower hydraulic loadings (0.16 m/hr and 0.08 m/hr) were selected for the proceeding runs in order to extend the duration of the operational cycle.

Hydraulic Loading: 0.16 m/hr (Run #7)

Upon termination of Run #6 the filter was cleaned

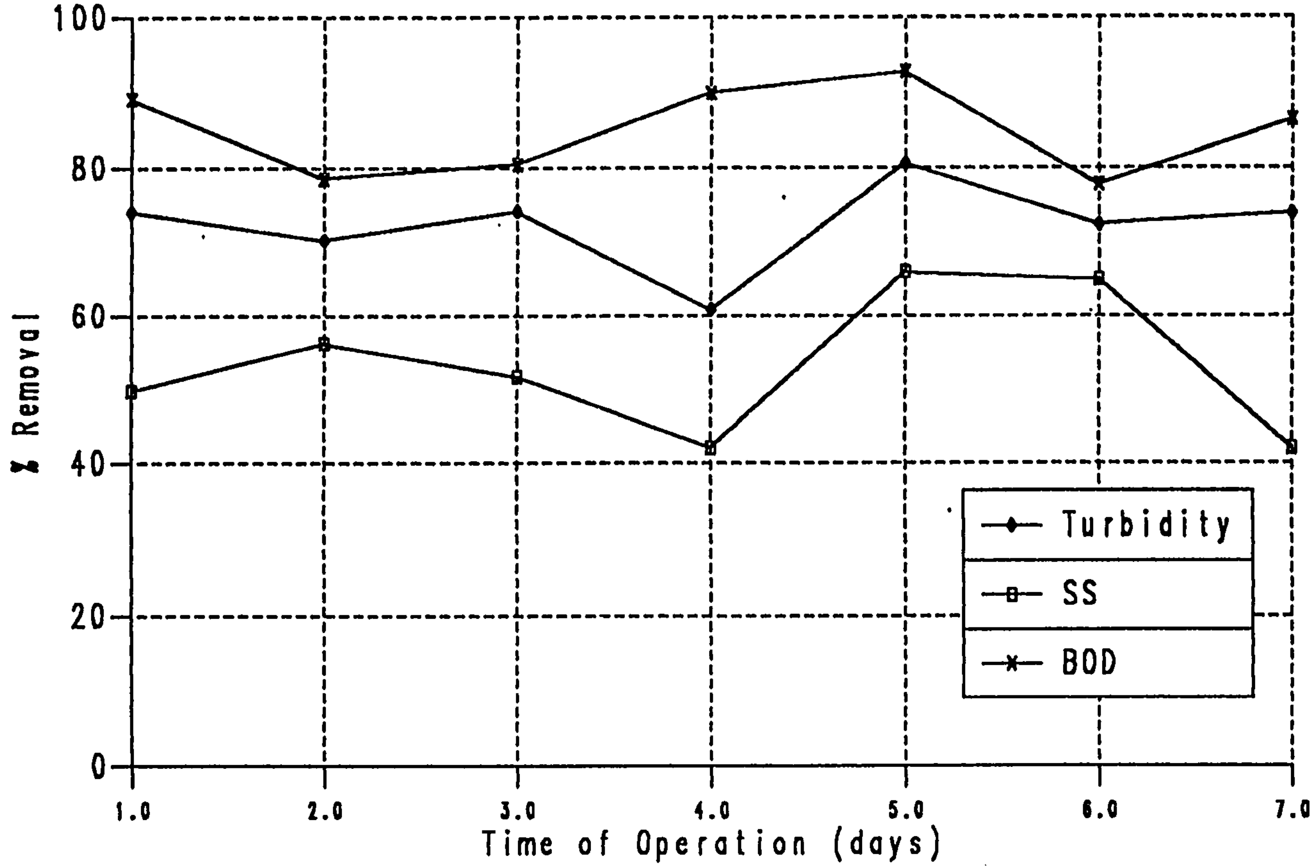

Figure 4.10: Removal of BOD, SS, and Turbidity (Run #6 , HL= 0.24 m/hr)

and reoperated at a hydraulic loading of 0.16 m/hr (corresponding to a flow rate of 2 L/min). The clean bed head loss was 12 cm which agrees well with the value computed from the Fair and Hatch equation (11.7 cm). In this run, the length of the operation extended to 12 days and the head loss accumulation over time is plotted in Figure 4.11. This figure also shows that very little head loss occurs between the bottom and the outlet manometer. In other words, the contribution of the lower part (i.e., 50 cm of sand, 40 cm gravel plus the underdrains and the control valve) to the head loss is minimal compared to the upper layers of the filter bed.

Initially the feed reservoir was visually observed to have a moderate concentration of algae, however, towards the end of this run they seemed to diminish, suggesting the start of a new "Substantial Succession" cycle. Table 4.7, gives the characteristics of the filter influent and effluent during this run while Figure 4.12 provides the bacteriological performance of the filter. The filter on the average removed 72.0,37.8,62.2 and 80.0% of BOD,COD,SS, and turbidity, respectively, during this run. Comparing these results with that of Run #5 and #6, it seems that both SS and

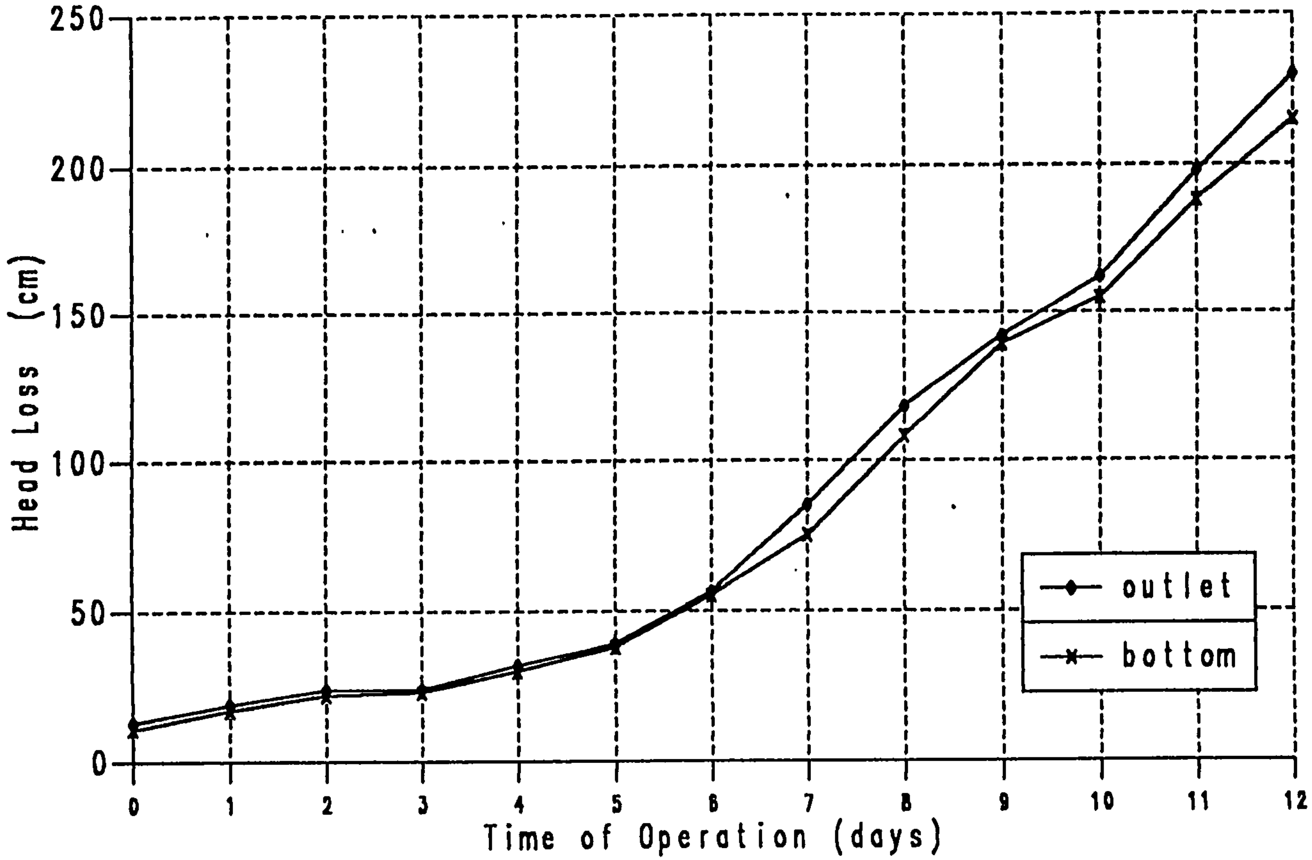

Figure 4.11, Head Loss Development Pattern (Run #7 , HL= 0.16 m/hr)

Table 4.7: Filter Performance (Run #7 , HL= 0.16 m/hr)

Parameter	No. of Samples	Influent		Effluent	
		Range	Mean	Range	Mean
Temperature , ^0C	12	19-23	21	19-23	21
pH	12	8.5-9.0	--	8.3-8.8	--
BOD, mg/l	12	1.4-3.3	2.5	0.1-1.3	0.7
COD, mg/l	12	29.6-48.1	38.6	13.5-40	24
DO, mg/l	12	10.2-13.9	11.9	3.1-10.1	6.7
SS, mg/l	12	10.7-19.8	14.3	2.9-10.0	5.4
Turbidity, NTU	12	1.2-1.8	1.5	0.2-0.6	0.2
Alkalinity,mg/l	6	99-107	104	90-105	99
Residual Chlorine, mg/l	6	0.30-0.50	0.35	0.20-0.30	0.25
Conductivity micromhos/cm	3	4900-5100	5000	4900-5100	5000

Remarks:
-bed depth: 88 cm
-clean bed head loss: 13 cm
-length of operation: 12 days

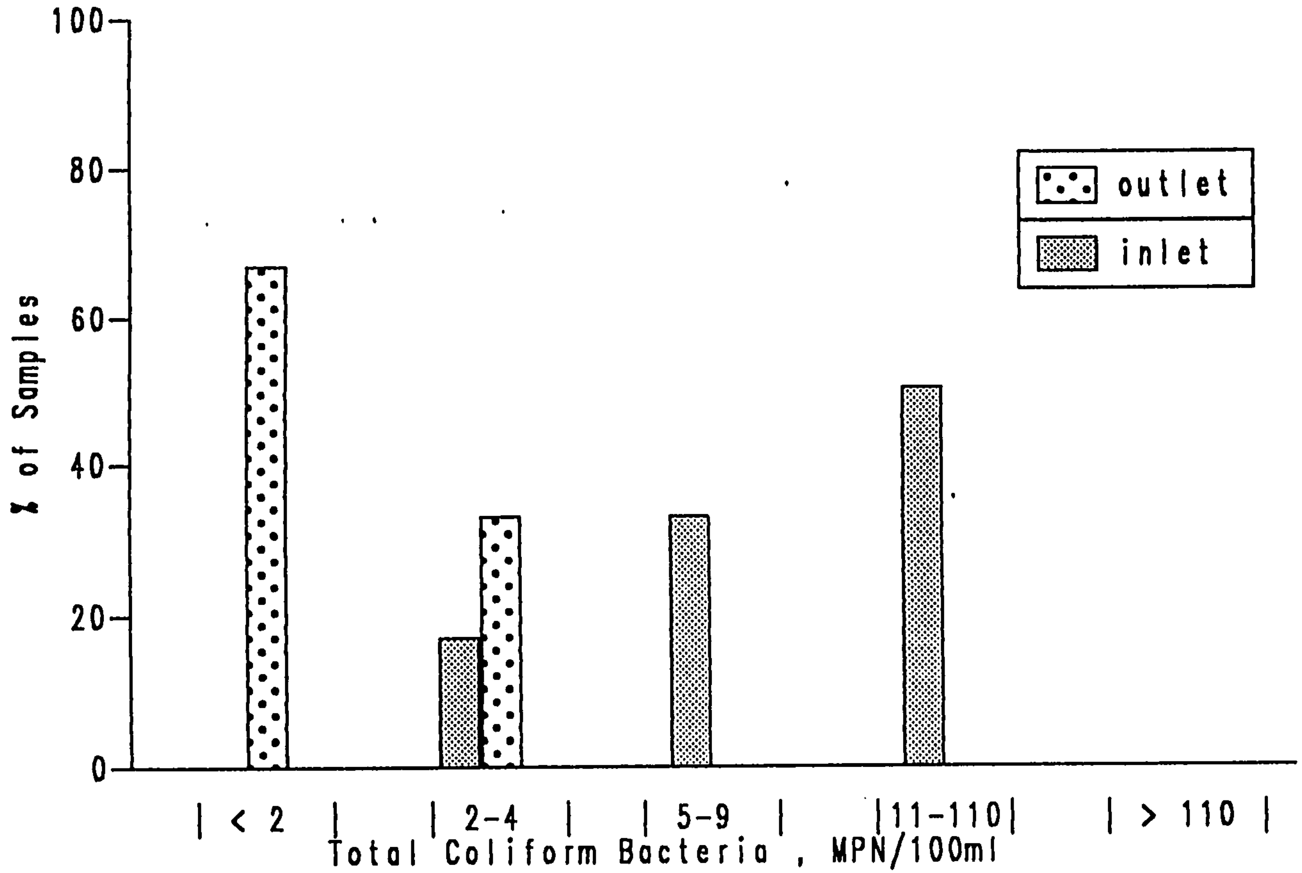

Figure 4.12: Bacteriological Performance (Run #7 , HL= 0.16 m/hr)

turbidity percent removals were higher. However, the BOD and COD percent removals were unexpectedly lower. The bacteriological performance of the filter at this run was very good as about 70% of the filter effluent samples were having an MPN of less than 2 per 100 ml. A drop of about 0.3 in the pH values, and thus a slight reduction in the alkalinity was observed. In summary, the system performed better at this hydraulic loading, especially in terms of turbidity and SS removal and a longer operational cycle. This is also evident from the daily variations of percent removal of BOD, SS, and turbidity as given in Figure 4.13.

Hydraulic Loading: 0.08 m/hr (Run #8)

Another operational run was conducted at a hydraulic loading of 0.08 m/hr (corresponding to a flow rate of 1 L/min). The operational cycle extended up to 42 days. The initial clean bed head loss was only 6 cm which once again agrees well with the Fair and Hatch value of 4.8 cm. Moreover, the operation continued virtually without any head loss build-up for about 28 days as shown in Figure 4.14. The major reason for this was at the beginning of the operational cycle the algal concentration in the feed reservoir was visually observed to decline due to the growth of rotifers which

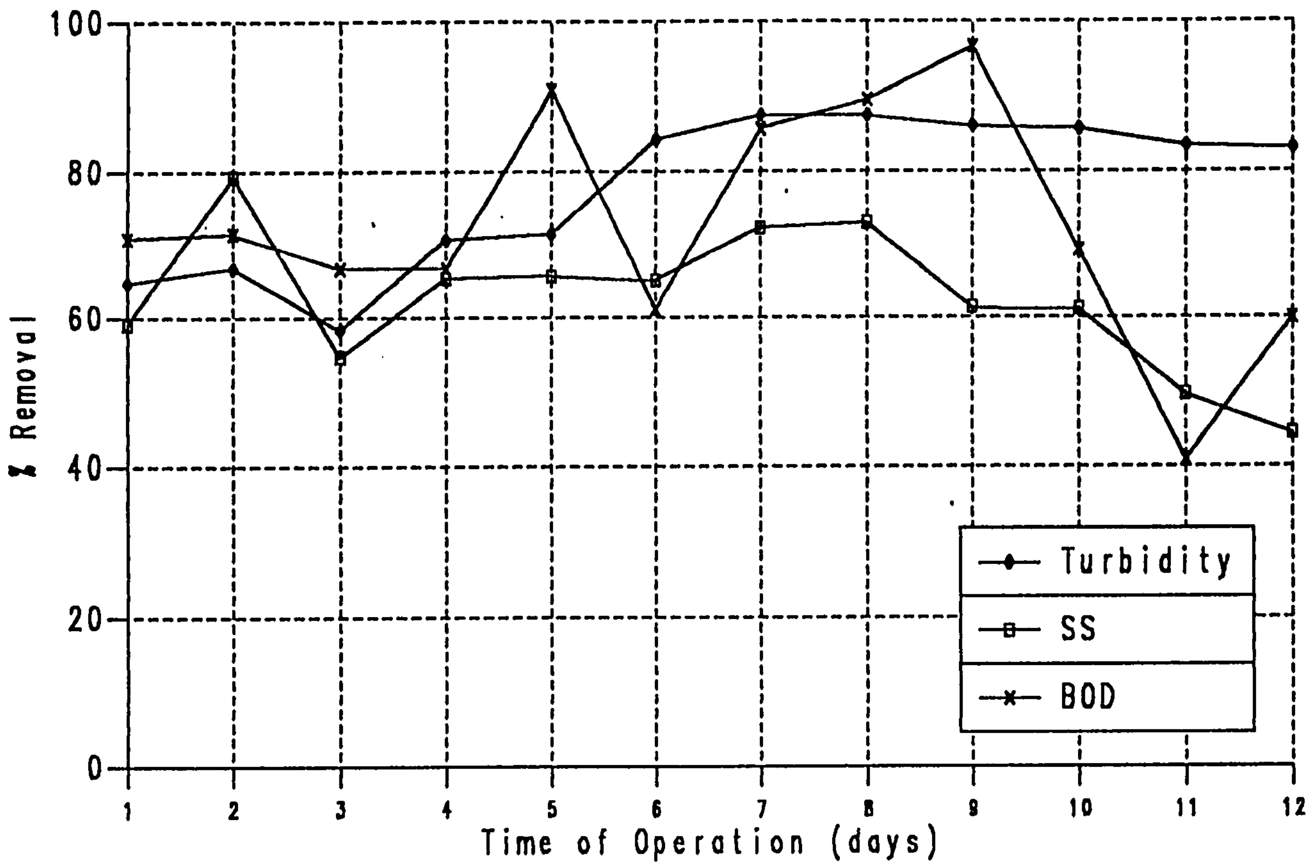

Figure 4.13: Removal of BOD, SS, and Turbidity (Run #7 , HL= 0.16 m/hr)

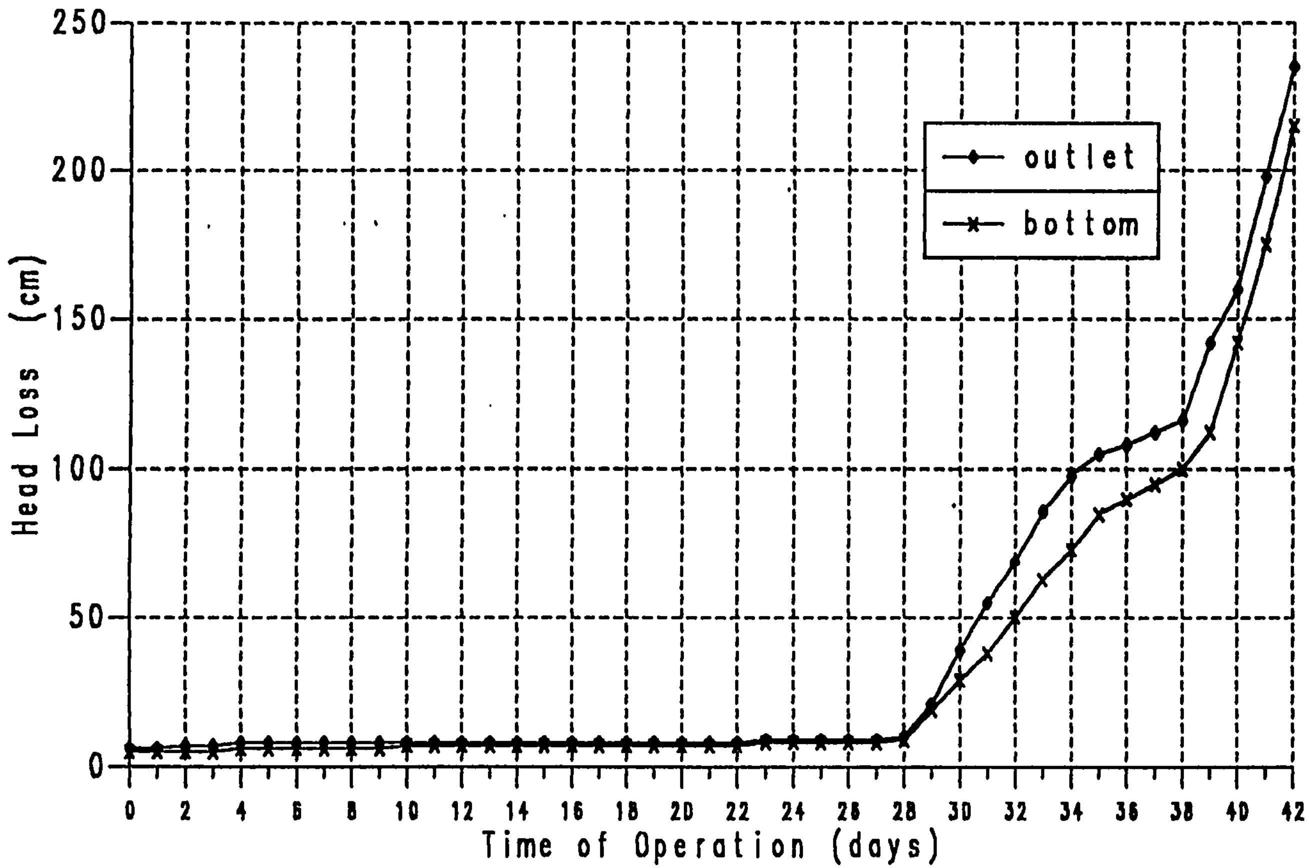

Figure 4.14: Head Loss Development Pattern (Run #8 , HL= 0.08 m/hr)

indicated yet another cycle of "Substantial Succession" of organisms. Table 4.8 summarizes the filter influent and effluent characteristics during this operational cycle while the bacteriological performance is shown in Figure 4.15. As observed from Table 4.8 the filter was able to remove 83.3, 18.5, 69.9, and 88.8% of BOD, COD, SS, and turbidity, respectively, on the average. Figure 4.15 shows that about 90% of the filter effluent samples were having an MPN of less than 2 per 100 ml eventhough about 85 % of the filter influent had an MPN of 11 to 110 per 100 ml. The daily variation of BOD,SS, .and turbidity for this run are shown in Figure 4.16.

In this run, several additional parameters were evaluated to have a wider picture about the process of slow sand filtration. It was observed that the sulfate concentration was always more in the filtered water while phosphate concentration was usually slightly less in the filtered water. The increase of sulfate in the filtered water is due to the biochemical oxidation of organic matter while the decrease of phosphate is most probably due to the removal of surface active agents.

As can be seen from Table 4.8, the nitrite (NO_2^-) and

Table 4.8: Filter Performance (Run #8 , HL = 0.08 m/hr)

Parameter	No. of Samples	Influent		Effluent	
		Range	Mean	Range	Mean
Temperature , ^0C	42	19-30	25	19-31	26
pH	42	8.5-9.1	--	8.1-8.7	--
BOD, mg/l	42	1.0-4.0	1.8	0.1-0.7	0.3
COD, mg/l	21	22.8-58.6	40.6	11.4-54.7	33.1
DO, mg/l	42	8.8-13.5	11.0	2.6-9.6	5.0
SS, mg/l	42	7.0-40.0	17.3	1.0-11.4	5.2
Turbidity, NTU	42	1.0-3.1	1.7	0.12-0.3	0.19
Alkalinity,mg/l	8	96-115	106	93-110	104
Sulfate, mg/l	6	533-587	560	587-640	620
Phosphate,mg/l	6	3.1-6.8	5.1	2.9-6.4	4.8
Residual Chlorine, mg/l	21	0.20-0.40	0.30	0.15-0.30	0.25
Conductivity micromhos/cm	8	4800-5300	5000	4800-5300	5000
Nitrite and Nitrate, mg/l	16	8.0-13.2	10.7	8.3-15.8	12.4
TKN:					
TON, mg/l	8	0.56-0.95	0.72	0.39-0.56	0.47
Ammonia, mg/l	8	0	0	0	0

Remarks:
-bed depth: 86 cm
-clean bed head loss: 6 cm
-length of operation: 42 days

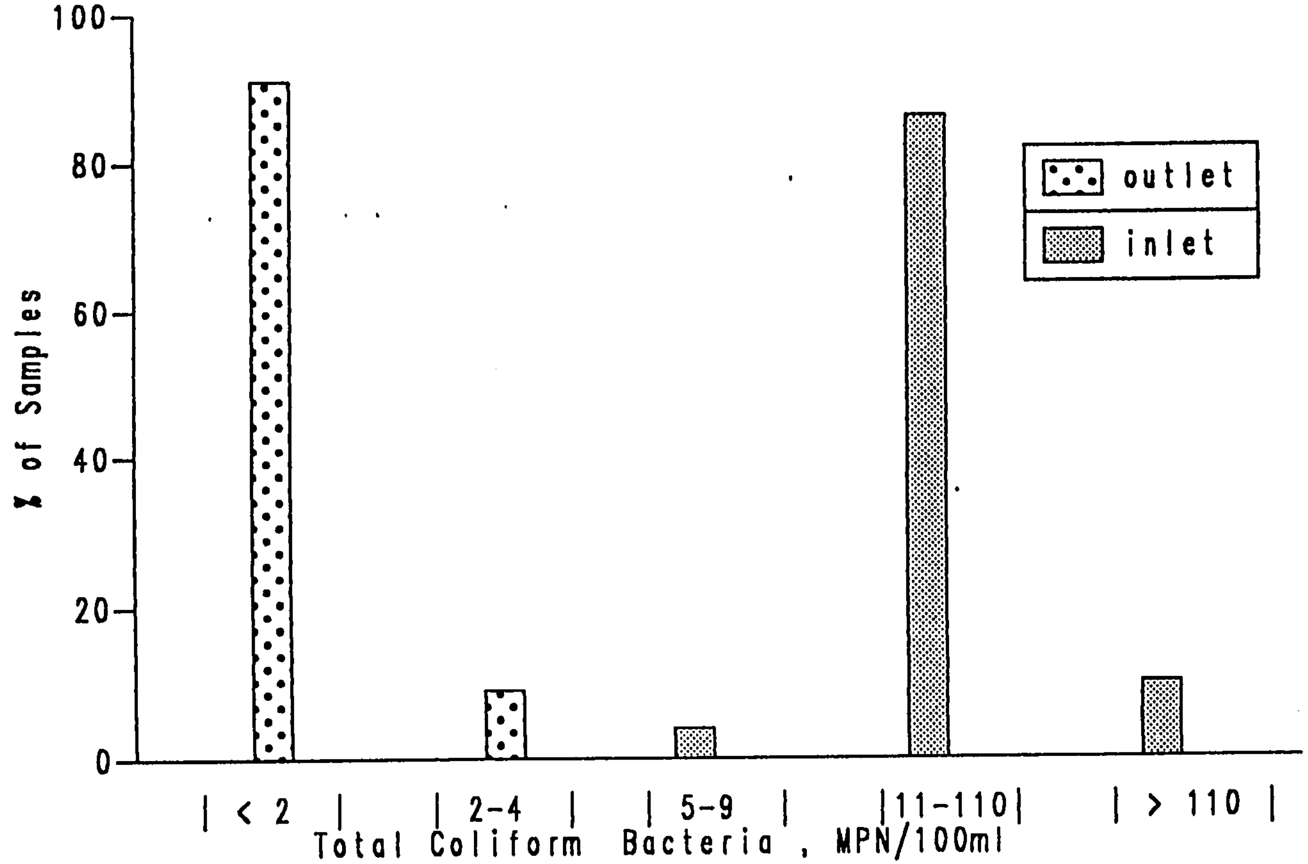

Figure 4.15: Bacteriological Performance (Run #8 , HL= 0.08 m/hr)

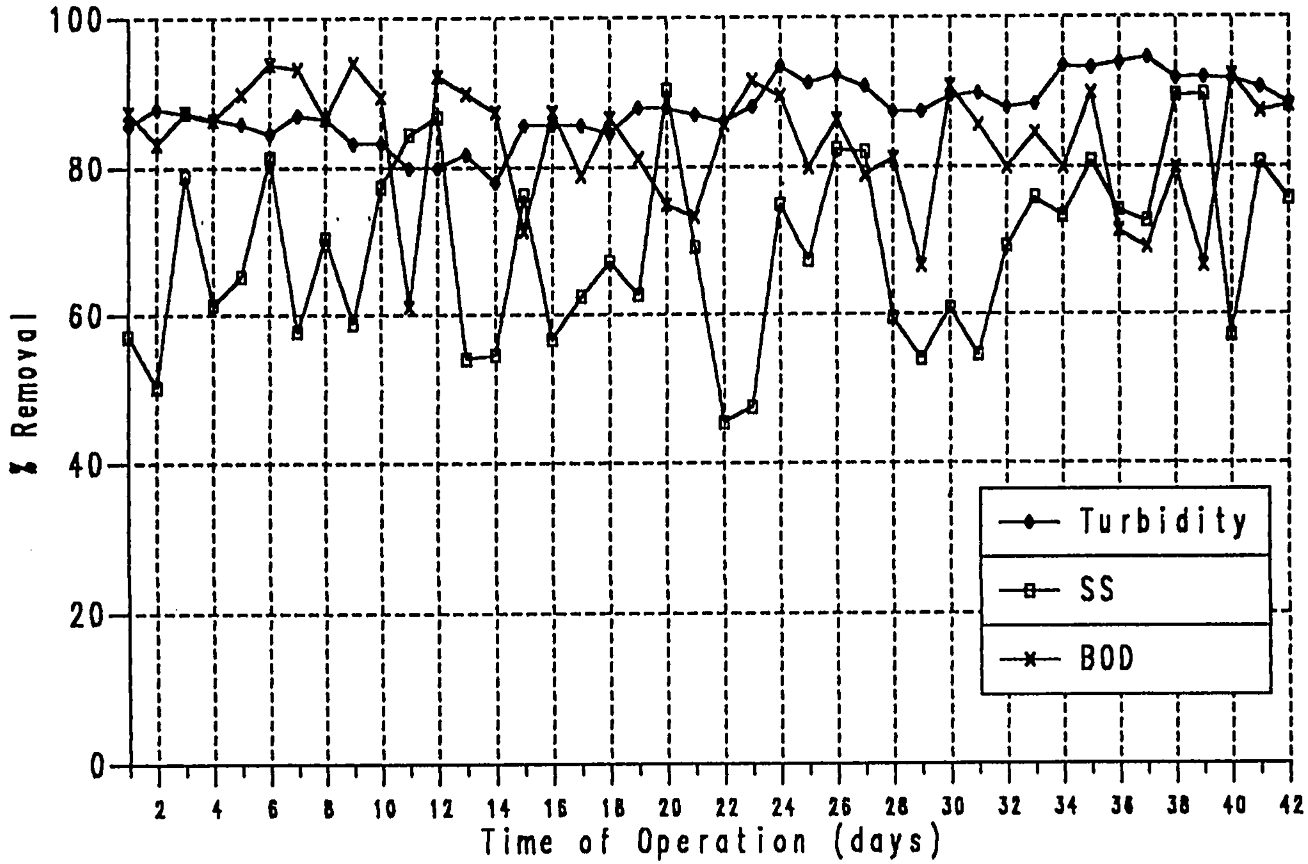

Figure 4.16: Removal of BOD, SS, and Turbidity (Run #8 , HL= 0.08 m/hr)

nitrate (NO_3^-) concentrations were higher in the effluent than the influent. Coupling this observation with a decrease in the DO and TKN (only organic nitrogen since ammonia is absent in the influent) indicates the occurrence of nitrification. This disagrees with the findings of Ellis(8). It must be pointed out, however, both observations are possible in view of the point raised by Scutt(30) as discussed in Chapter 2. That is, nitrification and denitrification in succession can occur within the filter bed. This point was further investigated in the next (final) run conducted in view of the previous experimental results.

4.4 FINAL RUN

All three hydraulic loadings studied, yielded a satisfactory removal with respect to BOD, SS, turbidity, and total coliform bacteria. As expected, the removal rate of SS and turbidity increased (almost linearly) by decreasing the hydraulic loading as shown in Figure 4.17. Apparently, this was also the case with total coliform bacteria. However, due to the very wide variation of the bacteriological quality of the filter influent during each run, the removal percentages would

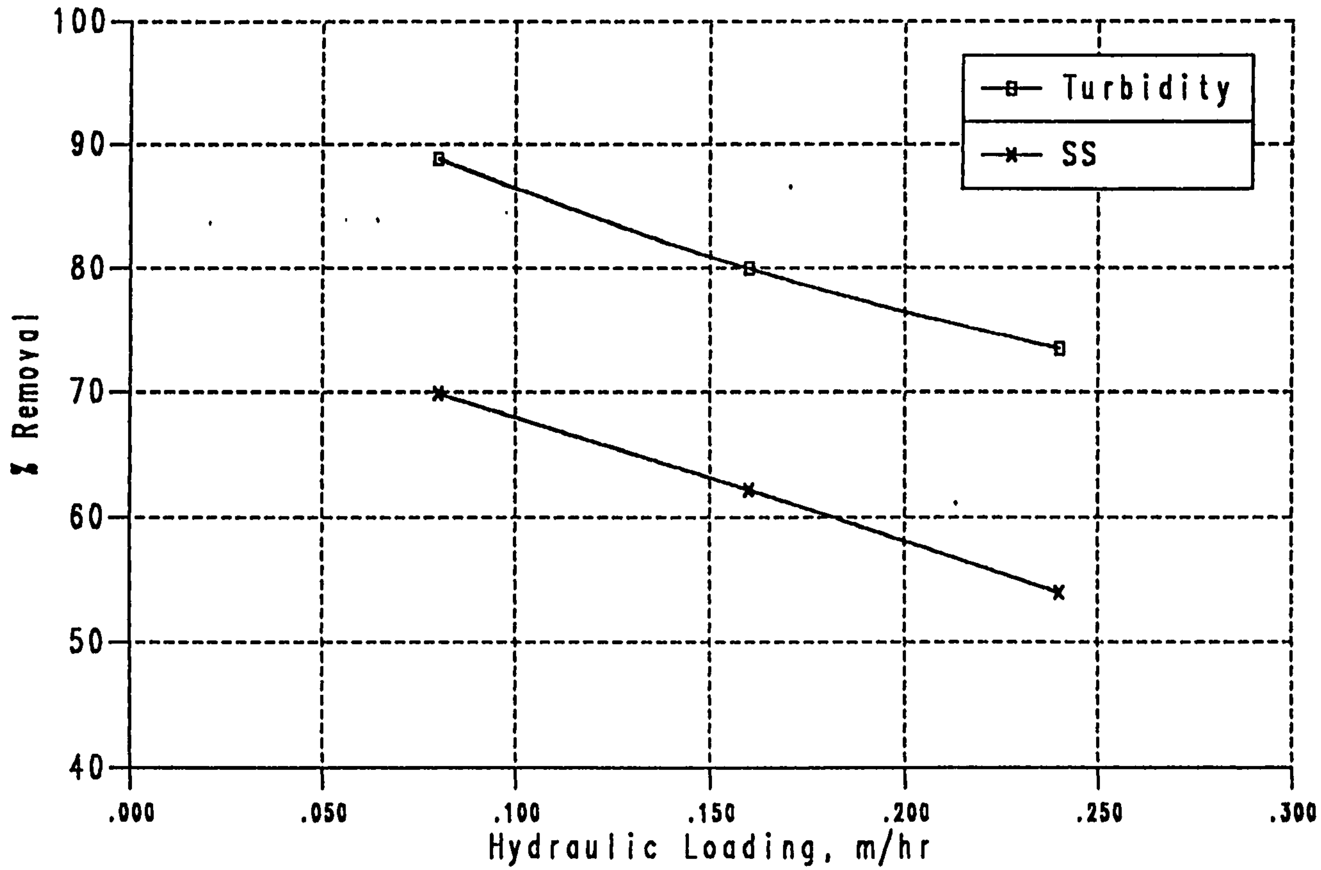

Figure 4.17: Effect of Hydraulic Loading on SS/Turbidity Removal

not be meaningful, thus they were not calculated. It is also thought that evaluating the hydraulic loadings should not be based on BOD removal percentage because the influent values are so low that the removal percentage is very sensitive to small variations. In summary, within the range of experimental values studied, the hydraulic loading does not seem to be a critical factor regarding removal of contaminants.

The run duration and the total quantity of wastewater treated per unit area over a year (i.e., the annual throughput) for different hydraulic loadings are summarized in Table 4.9 based on *Routine Runs*. As can be seen from this table, there is a tradeoff, as expected, between the hydraulic loading (i.e., land area requirement) and the volume of wastewater treated. For example, if labor is cheap and abundant and/or land area is a problem, a high hydraulic loading such as 0.24 m/hr should be selected. However, a high hydraulic loading will require frequent cleaning which may cause problems due to the interruption of the operation at a full-scale plant. On the other hand, a low hydraulic loading such as 0.08 m/hr would require larger (i.e., three times) land area which may cause difficulties in controlling the operation of the slow sand filter. Hence,

Table 4.9: Total Expected Annual Throughput

Hydraulic Loading, m/hr	Duration (days)	Number of Cleanings	Throughput* (m^3/m^2/year)
0.24	9	41	1630
0.16	12	30	1170
0.08	42	9	666

* assuming each cleaning would require two days

it is believed that a hydraulic loading of 0.16 m/hr would be a good compromise. Therefore, the final run (Run #9) was conducted at this loading.

During this run the algal concentration in the feed reservoir was visually observed to be low, which allowed for a longer filtration cycle (i.e., a period of 20 days compared to 12 days in Run #7). The clean bed head loss was 9 cm which is again close to Fair and Hatch value of 8.3 cm. The head loss build-up over time is given in Figure 4.18 which shows that a significant head loss was not observed until the 12th day of operation. Table 4.10 summarizes the characteristics of the filter influent, bottom sampling port , and effluent. Overall, a better performance was observed in this run as compared to Run #7. This is mainly due to the lower algal concentration in the feed reservoir and the higher ambient temperature. The average removal of BOD, COD, SS, and turbidity was 86.0, 35.4, 68.8, and 87.5, respectively. Figure 4.19 shows the bacteriological performance of the filter during this run. It is observed from this figure that all of the effluent samples had an MPN of less than 2 per 100 ml which shows the excellent ability of slow sand filtration in removing total coliform bacteria. Figure 4.20 provide the

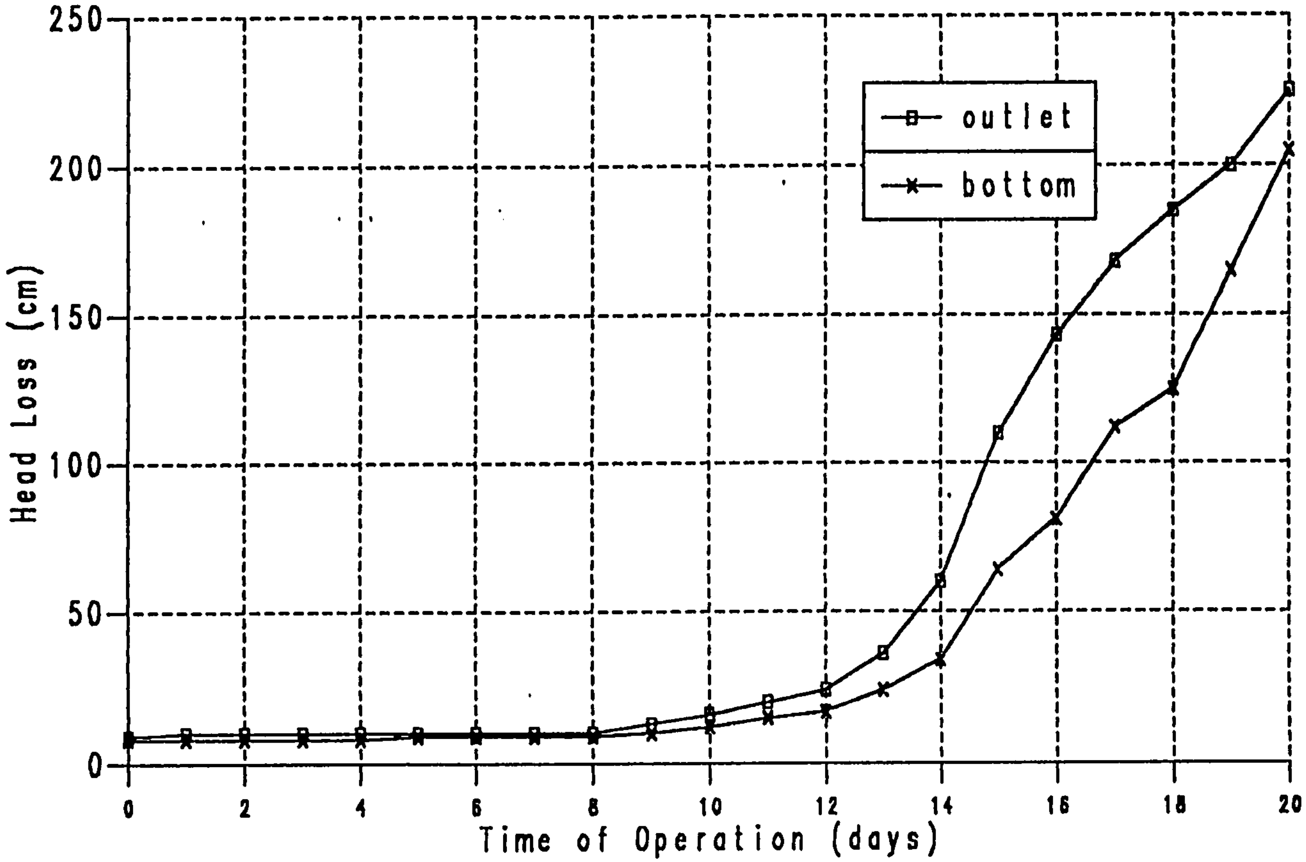

Figure 4.18: Head Loss Development Pattern (Run #9 , HL= 0.16 m/hr)

Table 4.10: Filter Performance (Run #9 , HL = 0.16 m/hr)

Parameter	Number of Samples	Influent Range	Influent Mean	Sample Port Mean	Effluent Range	Effluent Mean
Temperature , ^{0}C	20	30-34	32	--	31-35	33
pH	20	8.6-9.0	--	--	8.4-8.6	--
BOD, mg/l	9	1.3-4.0	2.5	--	0.2-0.7	0.35
COD, mg/l	9	27.2-44.9	37.0	27.5	19.4-30.0	23.7
DO, mg/l	20	10.0-13.0	11.0	--	5.7-7.0	6.2
SS, mg/l	20	10.4-36.0	23.4	10.7	2.5-12.0	7.3
Turbidity, NTU	20	0.9-2.0	1.2	0.3	0.11-0.26	0.15
Alkalinity,mg/l	6	102-108	104	--	100-104	102
Sulfate, mg/l	6	533-633	588	626	587-680	642
Phosphate,mg/l	6	4.1-6.6	5.3	--	3.1-6.7	4.9
Residual Chlorine, mg/l	9	0.25-0.40	0.30	--	0.15-0.30	0.20
Conductivity micromhos/cm	6	4100-4500	4300	--	4100-4500	4300
Nitrite and Nitrate, mg/l	9	7.0-13.7	9.1	12.9	7.5-14.5	11.1
TKN:						
TON, mg/l	4	0.67-1.12	0.90	--	0.45-0.65	0.51
Ammonia, mg/l	4	0	0	--	0	0

Remarks:
-bed depth: 84 cm
-clean bed head loss: 9 cm
-length of operation: 20 days

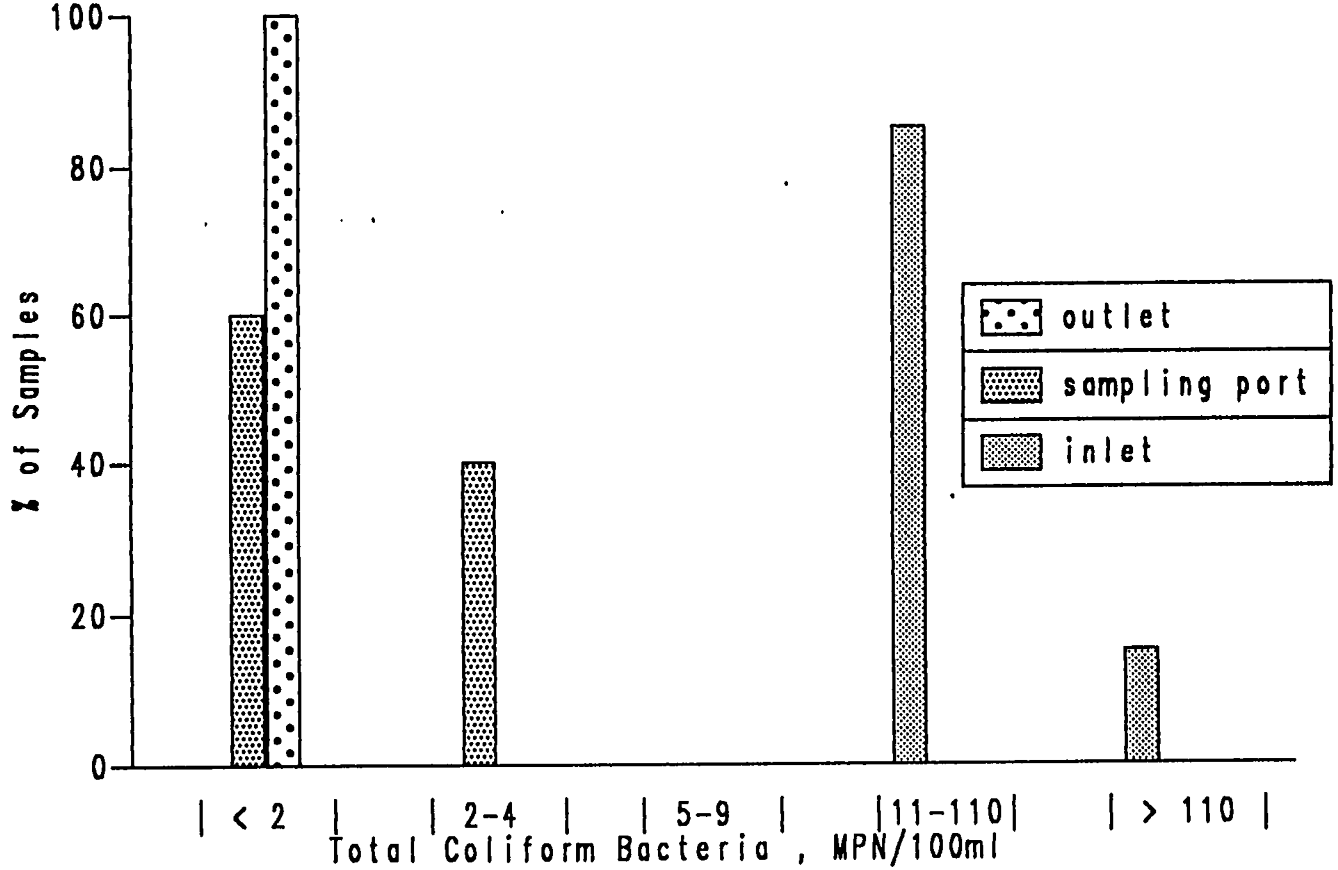

Figure 4.19: Bacteriological Performance (Run #9 , HL= 0.16 m/hr)

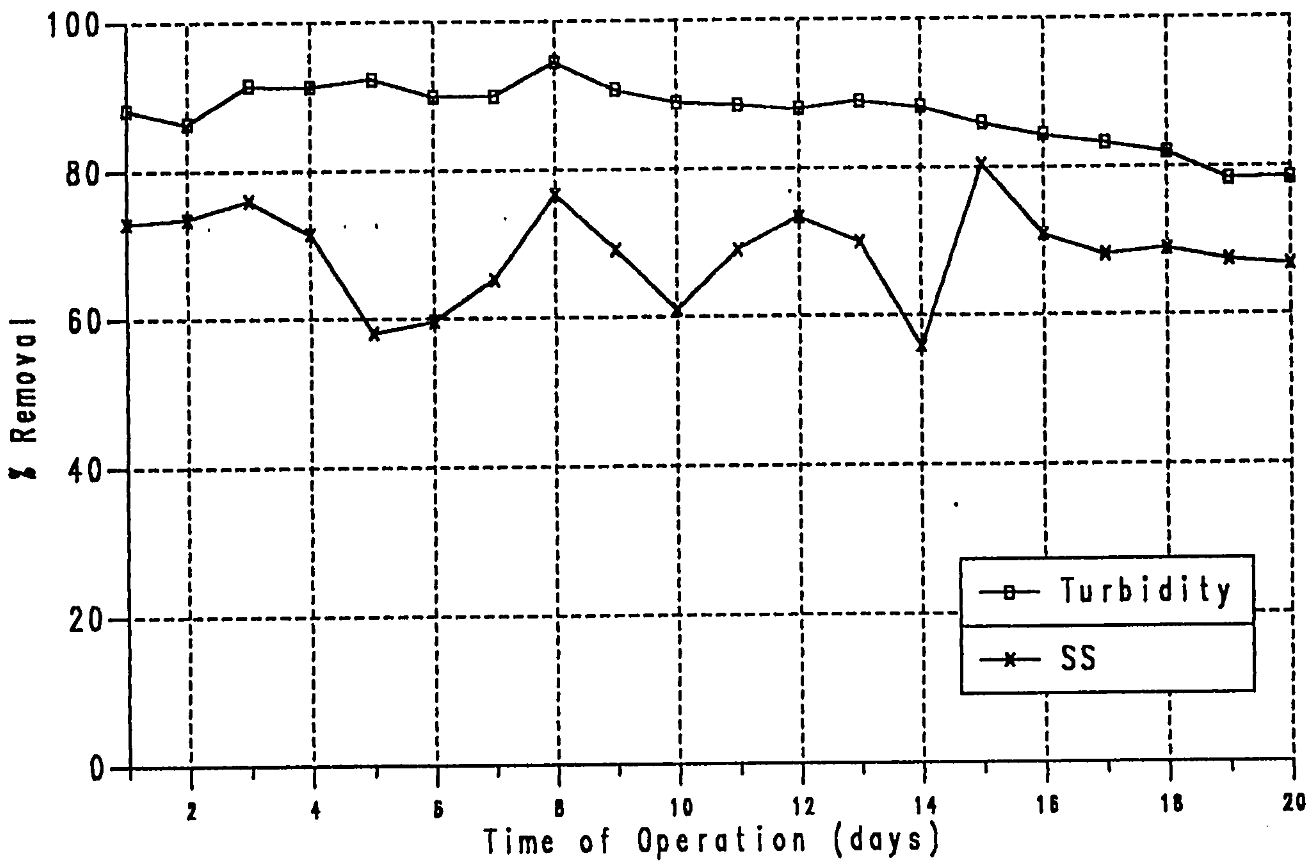

Figure 4.20: Removal of SS and Turbidity (Run #9 , HL= 0.24 m/hr)

daily variation of SS and turbidity during this experiment. It is worth noting that a good removal of total coliform bacteria as well as turbidity and SS is achieved at the bottom sampling port (i.e., 34 cm depth). This observation is a confirmation of the widely quoted statement in the literature "In slow sand filtration purification is occurring at the top layer of the sand bed (i.e., Shcmutzdecke) "(14).

Another important observation is related to nitrification / denitrification phenomena taking place during the filtration. As can be seen from Table 4.10, the average NO_2^- and NO_3^- concentration at the bottom sampling port is higher than that in the influent indicating that nitrification is probably taking place at the upper layers of the sand bed. This observation is reasonable since adequate oxygen is present at the upper layers of the filter bed and the Shcmutzdecke is rich with nitrogenous organic matter. However, deeper in the filter DO concentration decreases, thus denitrification is more likely to occur. Indeed, this is the case when it is observed from Table 4.10 that the NO_2^- and NO_3^- concentrations in the filter effluent is lower than that in the samples from the sampling port. Evidently, Scutt's(30) hypothesis on the subject discussed in Chapter 2 is verified. It should be pointed out, however, in this study it seems the degree of denitrification at the lower layers of the sand bed was lower than the degree of nitrification at the upper layers when qualified in terms of NO_2^- and NO_3^- concentrations. On the other hand, most probably the opposite was true in Ellis'(8) study.

4.5 MICROFLORA AND FAUNA OF THE SCHMUTZDECKE

During the investigation program it was decided to analyze the biota of the Schmutzdecke. Hence, upon termination of one of the routine runs, a dredge sample was obtained from the Schmutzdecke with the least amount of sand media for determining its constituents. The Schmutzdecke was very thin (about 0.5 cm) and its color was olive green. A very small portion was cleaned from attached sand particles and suspended in distilled water. An aliquot was drawn into a Sedgewick-Rafter cell for qualitative enumeration under the microscope with different degrees of enlargement while the organisms were alive. Positive identification of microflora and fauna was made on samples fixed with 10% formalin.

Table 4.11 shows the microflora and fauna that were present in the Schmutzdecke.

Algae were the predominant organisms in the Schmutzdecke. It was dominated by diatoms such as **Navicula**, however, there were also other types as shown in Table 4.11. On the other hand, several types of organisms were present on the Schmutzdecke under the microfauna category. Protozoa were mainly represented by the free swimming ciliates and crawling types like **Amoeba proteus**. In terms of biomass rotifers, particularly **Brachionus calyciflorus** was the major type. Ostracods like **Stenocypris** was also present in significant quantities. The flying insects mainly occupied the surface of the Schmutzdecke as zoobenthos were represented by the larval forms of **Diptera-Chironomus tentans**. These larvae occupied the shells made of organic deposits and debris. These shells were present in large numbers which contributed in increasing the organic content of the Schmutzdecke. Finally, it was observed that the Schmutzdecke formed in wastewater filtration had similar microflora and fauna to that of formed in potable water filtration as reported in literature (7,14,33).

Table 4.11: Microflora and Fauna of the Schmutzdecke

Microflora	
Group	**Category**
Scenedesmus Navicula Nitzchia Pinnularia Cymbella Diatoma Chlorococcum	ALGAE
Microfauna	
Amoeba proteus Colpoda Vorticella Lionotus Stylonechia Prorodon	PROTOZOA
Brachionus clayciflorus Asplanchna intermedia Lecane buulla Rotaria rotatoria Hexarthra Spirodina	ROTIFERS
Stenocypris	OSTRACODE
Dorylaimus	NEMATODES
Aelosoma	OLIGOCHAETA
Chironomus tentans	INSECTA

Chapter 5

CONCLUSIONS

This study is a field evaluation of slow sand filtration of secondary effluents at pilot-scale. The filter unit was cylindrical in shape with a diameter of 1 m and a height of 3.4 m. The media used was local sand with an effective size of 0.23 mm and a uniformity coefficient of 1.9 . The initial depth of sand bed was 1.05 m. The filter was operated continiously for a period of seven months, from November to May. The filter influent was the secondary effluent taken from an extended aeration plant, namely, North ARAMCO Wastewater Treatment Plant in Dhahran. The operational mode was constant-head , constant-rate, the latter was achieved by manual adjustment of the outlet valve.

A total of nine sets of experiments were conducted and the major operational parameter considered was the hydraulic loading. The results of all of the experiments, covering a hydraulic loading range of 0.08-0.24 m/hr, showed that slow sand filtration is, indeed, a very effective tertiary treatment unit. In particular, the removal of bacterial contaminants was exceptional to an extent that the filter effluent would easily qualify for unrestricted irrigation. In view of the results, 0.16 m/hr is suggested as a suitable hydraulic loading for the design of similar systems in Saudi Arabia. At this hydraulic loading the average removals of BOD, SS, turbidity, and total coliform bacteria were 86, 69, 88 and over 99 %, respectively, and the length of the filtration run was 20 days. As reported in the literature (4,7,11,14,33), most of the purification was observed to occur in the top layers of the sand bed. For example, samples taken from the outlet, where the sand depth was 84 cm, was not significantly superior in quality than the samples taken from a sand depth of 35 cm. Therefore, it is believed that the minimum bed depth of 48 cm suggested in the literature(4) can further be lowered. Moreover, it was observed that most of the head loss accumulation occurs at the Schmutzdecke which also agrees well with literature.

Throughout the experimentation period it was noted that the presence of algae in the filter influent was a very critical operational condition which affected the filter performance. For example, a high algal concentration in the filter influent definitely resulted in a decrease in the duration of operation and deterioration of the filtrate quality. Hence, it is believed that control of algae is of utmost importance for successful operation of the unit. Conventional chemical methods such as addition of copper sulfate to the influent, or physical methods such as prevention of exposure of the influent to sunlight may be used, for this purpose. In this study, no particular effort was made to control algal growth. Therefore, the concentration of algae was governed by the ambient conditions. Most notably an inverse relationship was observed between the presence/ absence of rotifers and algae, a phenomena referred to as "Substantial Succession" of microorganisms. Another important observation was the necessity for immediate cleaning following termination of an operational cycle. Otherwise, that is, if the filter is left uncleaned for a period of few days, the bacterial quality of the filter effluent will be deteriorated significantly due to the fouling of the media. In such a case, the required time for filter recovery can be shortened by flushing out the media with clean water.

Finally, another important observation was to have nitrification and denitrification occurring in succession within the sand bed. This observation verified a hypothesis put forward by Scutt(30) on the subject.

REFERENCES

1- *Annual Operations Report of 1988 for North ARAMCO Wastewater Treatment Plant*, Environmental Division, ARAMCO, Dhahran, April 1989 .

2- Baumann, E.R., Willrich, T.L., and Ludwig, D.D.,"Effect of Prechlorination on Filtration and Disinfection," *Amer. Soc. Ag. Eng.*, p.62-208, 1962 .

3- Bellamy, W.D., Silverman, G.P., Hendricks, D.W., and Logsdon, G.S., "Removing Giardia Cysts with Slow Sand Filtration", *Journal AWWA*, Vol.77, No.2, p.52, February 1985 .

4- Bellamy, W.D., Hendricks, D.W., and Logsdon, G.S., "Slow Sand Filtration Influences of Selected Process Variables", *Journal AWWA*, Vol.77, No.12, p.62-66, December 1985 .

5- Bishop, S.L., and Behrman, B.W., *Filtration of Wastewater Using Granular Media*, paper presented at the 1976 Thomas R. Camp Lecture Series on Wastewater Treatment and Disposal, Boston Society of Civil Engineers, Boston, 1976.

6- Edmondson, W.T.,"Changes in Lake Washington Following an Increase in the Nutrient Income", *Verh. Int. Verein. Limnol.*, Vol 14, p.167-175, 1961

7- Ellis, K.V.,"Slow Sand Filtration as a Technique for the Tertiary Treatment of Municipal Sewages", *Water Research*, Vol.21, No.4, p.403-410, 1987 .

8- Ellis, K.V., *Slow Sand Filtration*, CRC Critical Review in Environmental Control, Vol.15, No.4, p.315-354, 1985.

9- Fair, G.M., Geyer, J.C., and Okun, D.A., *Water and Wastewater Engineering*, Vol.2, Wiley, New York, 1968 .

10- Goldman, C.R., and Horne, A.J., *Limnology* McGraw-Hill Book Company, 384pp, 1983 .

11- *Guidelines for Operation and Maintenance of Slow Sand Filtration Plant in Rural Areas of Developing Countries,* IRC Research & Demonstration Project on Slow Sand Filtration, Rijswijk, The Netherlands, January 1983 .

12- Hansen, S.P., "Filtration Technologies for Water Treatment" *Water Engineering and Management,* p.16-22, August 1988 .

13- Holtz, R.D., and Kovacs, W.D., *An Introduction to Geotechnical Engineering,* Prentice-Hall, Inc., Englewood Cliffs, N.J. 07632, 1981 .

14- Huisman, L., and Wood, W.E., *Slow Sand Filtration,* World Health Organization, Geneva, 1974.

15- Hutchinson, R., *Treatise of Limnology,* John Wiley and Sons, Inc,New York, 1965.

16- Ives, K.J., *Filtration of Water and Wastewater,* CRC Crit. Rev. Enviro. Control, Vol.4, p.293, 1971 .

17- Kershaw, M.A.,"Tertiary treatment of Sewage Effluents", *Process Biochemistry,* Vol.11, p.21-35, 1976 .

18- Lack, R.J. and Collingwood, R.W.,"The Control of Reservoir Water Quality by Engineering Methods: The Effects of Storage on Water Quality", *Water Research Center Symposium,* Session 4, paper 18, 27pp, 24-26 March, 1975.

19- Letterman, R.D.,"An Overview of Filtration", *Journal AWWA,* Vol.21, No.12, p.26-37, December 1987 .

20- Mara, D., *Sewage Treatment in Hot Climates,* John Wiley and Sons, Inc., London, 1976 .

21- Metcalf and Eddy, Inc., *Wastewater Engineering: Treatment, Disposal and Reuse,* Second Edition, McGraw-Hill, Inc., New York, 1979.

22- O'Connor, J.T., *Environmental Engineering Unit Operations and Processes Laboratory Manual*, Association of Environmental Engineering Professors, July 1972.

23- Paramasivam, R., Mhaisalkar, V.A.,and Berthouex, P.M., "Slow Sand filter Design and Construction in Develo- ping Countries", *Journal AWWA*, Vol.73, No.4, p.178-185, April 1981 .

24- Poynter, S.F.B., and Slade, J.S.,"The Removal of Viruses by Slow Sand Filtration", *Prog. Water Technol.*, Vol.9, p.75, 1977 .

25- Pullen, K.G.,"Methods of Tertiary Treatment(2): Slow Gravity Sand Filters", *Pollution Monitor*, Vol.11, p.14-16, 1976 .

26- *Reuse of Effluents: Methods of Wastewater Tratment and Health Safeguards*, (Tech. Rep. Series No.517); World Health Organization, Geneva, 1973 .

27- Reynolds, T.D., *Unit Operations and Processes in Environmental Engineering*, Brooks Cole Engg. Div., PWS Publishers, Boston, 1982 .

28- Russell, J.S., Middlebrooks, E.J., Lewis, R.F.,and Barth, E.F.,"Lagoon Effluent Polishing with Intermittent Sand Filters", *Journal of Environmental Engineering, ASCE*, Vol.109, No.6, p.1333-1353, December 1983 .

29- Schulz, C.R. and Okun, D.A., *Surface Water Treatment for Communities in Developing Countries*, Wiley-Interscience, John Wiley and sons, New York, 1984.

30- Scutt, J.E., Comment on "Slow Sand Filtration as a Technique for the Tertiary Treatment of Municipal Sewage", *Water Research*, Vol.23, No.3, p.397, 1988 .

31- Seelaus, T.J., Hendricks, D.W.,and Janonis, B.A., "Design and Operation of a Slow Sand Filter" *Journal AWWA*, Vol.76, No.12, p.35-41, December 1986 .

32- *Slow Sand Filtration: Research and Demonstration Project, India*. National Environmental Engineering Research Institute (C.S.I.R.), Nagpur, India, and IRC for Community Water Supply and Sanitation, The Hague, The Netherlands, 1982 .

33- *Slow Sand Filtration: Small Community Water Supplies*, IRC for Community Water Supply and Sanitation, The Hague, The Netherlands, February 1986

34- *STANDARD METHODS for the Examination of Water and Wastewater*, 15th Edition, APHA, AWWA, and WPCF, Washington, D.C., 1980 .

35- Task Committee on Design of Wastewater Filtration Facilities, "Tertiary Filtration of Wastewater", *Journal of Environmental Engineering, ASCE*, Vol.112, No.6, p.1109-1025, December 1986 .

36- Tchobanoglous, G., and Elliasen, R.L.,"Tertiary Filtration of Activated Sludge Effluent", *Journal of the Sanitary Engineering Division, ASCE* Vol.96, SA2, p.243, April 1970.

37- *Third Development Plan, 1980-85*, Kingdom of Saudi Arabia, Ministry of Planning Press, Riyadh, Saudi Arabia, May 1980 .

38- Truesdale, G.A., Birkbeck, A.E.,and Shaw, D.,"A Critical Examination of Some Methods for Further Treatment of Effluents from Percolating Filters", *Journal of Institution of Sewage Purification*, Vol.63, p.81-101, 1964 .

39- Viessman, W., and Hammer, M., *Water Supply and Pollution Control*, Fourth Edition , Harper and Row Publishers, New York, 1985 .

40- Weber, W.J., *Physicochemical Processes for Water Quality Control*, John Wiley and Sons, Inc, New York, 1972 .

41- Wetzel, R.G.,"Productivity Investigations of Water Connected Marl Lakes", *Hydrobiological Studies*, Praha, Vol.3, p.91-143, 1973 .